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Markerless Radiostereogammetry of the Shoulder Joint in Humans: Comparisons of Scapulohumeral Kinematics Between Individuals with Healthy and Supraspinatus-Impaired Shoulders

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Abstract

The purpose of this collection of studies was to further develop the knowledge of shoulder motion in order to better understand joint function through direct measurement of 3D scapulohumeral joint kinematics using a technique of high accuracy. Markerless, bi-planar fluoroscopic radiostereometric analysis using a generic shoulder model was developed in this thesis, reducing the amount of radiation exposure to subjects. The studies compared kinematic data of the scapulohumeral joint in six degrees of freedom with a precise, in-vivo measuring technique. Data were collected on young and older healthy individuals, individuals with a torn supraspinatus and post-surgical intervention.

Although this generic model method has higher error than other biplanar fluoroscopic techniques, it is still more accurate than skin-based motion capture techniques. Younger and older healthy groups have different scapulohumeral motion patterns for abduction, forward flexion and a more combined motion of arm across the chest. Major differences were noted during humeral abduction when comparing an age-matched controlled group to groups with injured supraspinatus muscles and post-surgical repair of the supraspinatus muscles. In the injured group, there is significantly higher scapulohumeral rhythm which is significantly lowered post-surgery.

These are the first studies of this nature using generic models to analyze scapulohumeral kinematics. Future research could include the evaluation of muscle function before and after repair in tandem with kinematic results and comparisons of the scapulohumeral kinematics between different surgical repair techniques. This information will allow clinicians to make more informed treatment plans based on the needs of each individual patient.

Keywords

The following keywords describe the thesis entitled “Markerless radiostereogammetry of the shoulder joint in humans: Comparisons between individuals with healthy and supraspinatus-impaired scapulohumeral kinematics ”: kinematics, biomechanics, shoulder, scapulohumeral joint, orthopaedic, rotator cuff repair, supraspinatus, radiostereogammetry analysis, fluoroscopy, motion, abduction, forward flexion, arm across chest, scapulohumeral rhythm, subacromial space.

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Glossary of Terms

Abduction	rotation away from the midline
Adduction	rotation towards the midline
Anterior	translation in the forward direction
Arm across chest	combined motion bringing the arm forward and tapping the hand on the moving arm on the opposing shoulder
Extension	rotation parallel to the midline in the back direction, creating a larger angle at the joint
External rotation	rotation away from the front of the body
Forward flexion	rotation parallel to the midline in the forward direction, creating a smaller angle at the joint
Glenohumeral joint	articulation between the glenoid fossa of the scapula and humeral head
Inferior	translation downwards, towards the feet
Internal rotation	rotation towards the front of the body
Kinematics	examination of movement from the perspective of time and space
Lateral	translation away from the midline
Medial	translation towards the midline
Midline	a theoretical line through dividing the body in half from the top of the head to the bottom of the feet

Pathology	examination of organs and tissues in order to diagnose medical conditions
Posterior	translation in the backward direction
Radiostereometric analysis	a technique for measuring kinematics of the skeletal system in 3D using two 2D perspectives
Roentgenography	using radiation to create images, also called radiography or x-ray imaging
Rotator cuff	muscles of support and function around the glenohumeral joint, including the infraspinatus, supraspinatus, teres minor and subscapularis muscles
Scapulohumeral rhythm	ratio of scapular motion to humeral motion
Skin motion artifact	error in measurement of bone kinematics when using superficial markers
Stereophotogrammetry	calibrating specific point to a 3D position from 2D perspectives
Superior	translation upwards, towards the head
Tendon	a fibrous connective tissue connecting muscle to bone

Chapter 1

1 Introduction

Human motion has been described for thousands of years. Several methods have been employed to investigate the movement of the shoulder. Understanding the role of the shoulder joint in a healthy population and how it compares to individual pathological conditions is important to enhance medical knowledge. This knowledge can be used to enhance current orthopedic techniques to assist in the return pathological movement healthy, normal movement. It is essential to understand the history of the kinematic analysis to be able to apply this knowledge to new techniques.

1.1 History of kinematic analysis

Kinematic analysis is the examination of movement from the perspectives of time and space, independent of motion-causing forces (Hamill and Knutzen, 2003, Winter, 2009). Aristotle made the first references to the analysis of gait hundreds of years before the Common Era. In his time, it was believed that problems were solved by thinking, not by experimenting, so his hypotheses were never evaluated (Baker, 2007). It was not until the European renaissance where increased knowledge of mathematics and science would allow for experiments to be conducted and appreciated by society. Borelli performed the first experiment in gait analysis involving walking poles (Baker, 2007). Borelli, considered the pioneer of modern biomechanics, also analyzed the motions of running, jumping, and skating (Clarys and Alewaeters, 2003). Although Newton did not contribute directly to the study of human movement, his laws of mechanics are keystones for current explanations of human motion. New technologies for human kinematic analysis have broadened this area of research.

In the mid-1800s, the Weber brothers did extensive work in the area of human movement analysis with the use of a stop watch, measuring tape and telescope (Baker, 2007, Mundermann, Corazza, and Andriacchi, 2006). One of the first methods of measuring movements of the body was in the late 1800s by Braun and Fisher (Baker, 2007). They applied illuminated tubes to the limb segments on the subjects. The subjects moved in total darkness and movements were captured through the use of interrupted light and photographs. Measurements in three dimensions were attainable using this technique (Baker, 2007, Mundermann et al., 2006, Sutherland, 2002). White light markers were placed on the surface of the body over the joint centres, motion was recorded on film and developed. The researchers would then measure the changes in the location of the marker between each frame of film (Sutherland, 2002). One of the main concerns with this approach is the inaccuracy of the marker system. Instead of being attached to bone directly, the markers are attached to the skin. Inman and Eberhart used cine photography and interrupted light photography for much of their work (Baker, 2007, Sutherland, 2002). One of the next tools for examining human motion was the use of bone pins drilled directly into the bone, minimizing marker movement (Levens, Inman, and Blosser, 1948). This allowed more accurate calculation of the joint motion than past estimates, however, this intrusive method caused pain in the subjects and is not used often in movement analysis today (Sutherland, 2002).

Murray included manual goniometric measurements in her research throughout the 1960s. The Karpovich brothers created accurate, inexpensive and simple electrogoniometers, which eased the painstaking manual task and drastically reduced the time of data processing (Sutherland, 2002). The next tool for easy and accurate motion analysis was the Vanguard Motion Analyzer. This device allowed the user to analyze each frame of film in two-dimensions with a backlit screen. In 1965, Ray Linder published a methodology using a two-dimensional coordinate system to measure the three-dimensional rotations of yaw, pitch, and roll (Sutherland, 2002).

Over time, computers became more powerful and camera quality improved. These tools were developed as aids to analyze data quickly. A fully automated motion capture system called VICON was created. This system simplified data collection and movement analysis, and also minimized the time spent analyzing data (Sutherland, 2002). ELITE, another motion capture system, was able to combine kinematics, kinetics and electromyography to analyze gait and motion (Sutherland, 2002).

Marker based motion capture systems are convenient and fairly simple to use (Mundermann et al., 2006). Data from skin mounted tracking systems can be processed quickly and have sub-millimeter accuracy (Massimini, Warner, Li, and Guoan, 2011). These markers can be either passive reflective or active infrared in design and are placed on the skin to infer underlying motion between segments, defining joint motion (Mundermann et al., 2006). With these techniques, it is assumed that a marker attached to the skin moves equally to the underlying bone; however, it is known that the skin underneath a marker attachment site can deform and translate differently than the underlying bone and muscle contractions can also cause inaccurate measurements (Barré, Jolles, Theurmann, and Aminian, 2015, Kedgley, 2009). Skin motion artifact limits the accuracy of these motion data collected when using skin-based markers for motion capture (Mell et al., 2005).

A number of motion capture technologies exist. Bone pins and external fixation devices are able to measure motion of the bones that they are implanted into. These techniques are invasive and may limit extreme motions by preventing skin motion over the bone, and is one of the reasons these techniques are not always employed (Massimini et al., 2011). Cappozzo, Catani, Leardini, Benedetti, and Della Croce (1996) compared measurements using skin-based markers and external fixators on the femur or tibia. Differences in displacement between the two techniques ranged from a few mm up to 40 mm. Trajectory errors may not seem substantial when measuring broad movement patterns, however, from a clinical perspective, these errors in the measurements of motion could be considerable.

A recent development in data collection is the radiostereometric analysis (RSA) technique for measuring kinematics of the skeletal system. Selvic (1989) created a RSA protocol that was accurate between 0.05 mm and 0.5 mm for translations and between 0.15˚ and 1.15˚ for rotations. This method creates coordinates in 3D based on the 2D images captured through roentgenography (radiography) (Selvic, 1989).

The RSA technique involves collection of an object using two-dimensional radiography images from two perspectives. In order to manipulate the images into 3D for analysis, an image registration technique must be employed. This process aligns the two images so certain features on the object can be related within both images (Edwards, Hawkes, Penney, and Clarkson, 2001). In more current terms, it also refers to alignment of a computer model, or features in an image, with locations in the physical or virtual environment. For example, each point of the CT image will correspond to a specific location found on each fluoroscopic image. This specific point from 2D perspectives can be calibrated to a 3D position, called stereophotogrammetry (Hawkes, 2001). The correspondence of this spatial information is fundamental for medical image interpretation and data analysis (Hawkes, 2001).

There are two classes of the stereophotogrammetry method. The first is called feature-based and the second is called direct intensity (Hawkes, 2001). There are several feature-based techniques which use silhouettes of bony structures to relate specific points from images. Algorithms aligns these pre-determined structures found in the x-ray images to the corresponding projection surface of the captured CT volume. The methods of this feature-based class include the head and hat algorithm, distance transforms and the iterative closest point algorithm (Hawkes, 2001).

The head and hat algorithm determines the "head" as the 3D image and the points of the additional image capturing modality as the "hats". Combinations of the 3D image positioning with the 2D images are performed until the best hat on head fit is determined by calculating the minimum sum of squared differences between each point of the hat with the head (Hawkes, 2001). This is not an ideal algorithm because it the minimum sum of squares may not accurately reflect the landmarks and unique geometries of the bones being matched. This technique can also fail when there are symmetries in rotation along the surfaces of the head and hat structures (Hawkes, 2001).

Distance transforms use a different method of calculation of best fit for the 3D and 2D images. This method is more efficient because it uses pre-computed distances from every point in space to one of the surfaces being registered, making this technique a faster approach to 3D image registration (Hawkes, 2001).

The iterative closest point algorithm uses a set of points representative of one surface and "facets", or triangular patches, representing the other surface. A pre-determined closest point distance is found on the appropriate facet with respect to each of the points. The closest distance between points and facets form a set. This location is registered with the corresponding landmarks in 3D and the residual error is calculated. From this new set of data, another iteration of closest points is calculated until the residual error is less than the pre-set value (Hawkes, 2001). This process often requires manual adjustments. A way to minimize manual editing is through the use of intensity based 2D to 3D registration. This technique matches pixel and voxel intensities of the images directly using digitally reconstructed radiographs (Edwards, 2001).

The RSA procedure developed by Kedgley (2009) used a manual 2D to 3D registration technique to measure scapulohumeral kinematics. This invasive technique included the implantation of tantalum beads into the scapula and humerus of the subject. These beads were implanted during surgical intervention for a rotator cuff injury. Following a brief recovery period, the subject underwent biplanar fluoroscopy to capture images of scapulohumeral motion (Kedgley, 2009). The case study yielded accurate results, but was invasive in nature through the use of radiation and bead implantation. A limitation with this technique is that it is not possible to obtain pre-surgical data because the beads must be implanted surgically.

In order to minimize invasiveness, Allen (2011) developed a markerless methodology based on the protocol for biplanar fluoroscopic RSA created by Kedgley (2009). Instead of relying on tantalum beads to measure motion, landmarks were digitized on a CT volume of the humerus and scapula of the subject according to landmarks of ISB protocol (Wu et al., 2005). The trajectories of these landmarks were used to calculate scapulohumeral motion. This study determined that the difference between using the markerless methodology and the standard RSA protocol created by Kedgley was minimal and there was an additional benefit of minimizing invasiveness by omitting the need for the implantation of beads into the bone (Allen, 2011). By omitting the implantation of beads into the bones of interest, it allowed for the ability to measure individuals that did not need a surgery, such as healthy, normal subjects.

The RSA approach to kinematic analysis involves exposure to radiation. Over the years, there has been substantial development of x-ray technology, minimizing the amount of radiation required for imaging. In addition, Fox et al. (2011) developed an alternative method and was able to reduce the CT radiation dose on cadaveric scapulae and humeri by 98% without introducing additional error. These advances in imaging technology makes measuring in-vivo kinematics of the shoulder using the RSA method much simpler while reducing the exposure to radiation and invasion of the subjects.

1.2 X-ray imaging

X-ray technology has been used since the discovery of fluorescence by Röentgen over 100 years ago (Iniewski, 2009). Immediately, the value of the x-ray was seen as an important tool in the medical field (Johnston and Fauber, 2012). This technology is still used today, in 2D and 3D configurations, to assist in medical diagnoses. X-ray imaging is based on the transmission and analysis of X-ray absorption and interaction with the anatomical point of interest. The image is created through the combination of a phosphor screen and light sensitive film (Iniewski, 2009, Johnston, 2012). X-ray image quality is dependent on tissue thickness, tissue density, and x-ray beam quality (Johnston and Fauber, 2010).

In today's digital world, fluoroscopy is used as a common x-ray imaging technique. Fluoroscopy allows for real time observation of x-ray images of the subject. The x-rays are projected through the patient and the fluoroscopic images created through this procedure contain information about internal anatomical structures (Edwards et al., 2001, Johnston and Fauber, 2012). The image intensifier is component of the fluoroscope used as a transition stage, supplying signals to complementary metal oxide semiconductor (CMOS) cameras, producing an analog image on a TV screen. Also, the image intensifier creates a brighter image for viewing and decreases the amount of radiation exposure (Iniewski, 2009, Johnston and Fauber, 2012).

Distortion of the collected image is a misrepresentation of the size or shape of the object captured within the radiograph (Johnston and Fauber, 2012). Size distortion or magnification refers to an increase in size of the anatomical part being imaged. The two causes of size distortion are the distance between the x-ray source and the image receptor and the distance between the object and the image. Although minimizing the distances of the x-ray source and object to the image receptor will help reduce size distortion, some parts of the object will always be further away from the image receptor than others. The parts that are further away from the image receptor will have more size distortion than the parts that are closer to the image receptor (Johnston and Fauber, 2012).

Shape distortion can appear through elongation or foreshortening. This occurs when there is inaccurate alignment with the central ray tube, the object to be imaged, or the image receptor when the image of an object is being captured (Johnston and Fauber, 2012).

Currently, the image captured through a fluoroscope is often viewed on a TV monitor. Images recorded from these monitors for analysis will also have distortion, called pincushion distortion. This distortion is a result of inaccurate focus of the x-ray electrons around the edges of the photocathode, leading to unequal magnification (Johnston and Fauber, 2012). Vignetting, a loss of brightness around the edges of the image, can also be caused by this distortion (Johnston and Fauber, 2012).

1.3 The shoulder complex

1.3.1 Anatomy

The bones of the shoulder complex include the humerus (upper arm), scapula (shoulder blade), and clavicle (collar bone; Figure 1-1). The shoulder has four different articulations: the sternoclavicular, acromioclavicular, scapulothoracic and glenohumeral joints. Some of the scapular joints can be viewed below (Figure 1-2). These joints work simultaneously to create movement (Tortora, 2002, Inman, Dec, Saunters and Abbot, 1944). The rotator cuff muscles (supraspinatus, infraspinatus, teres minor and subscapularus) are the main muscles of the shoulder complex, and can be seen in Figure 1-3. Although ligaments provide some support of the joint, the main support component of the shoulder complex is its surrounding musculature (Nishinaka et al., 2008, Tortora, 2002, Inman et al., 1944).

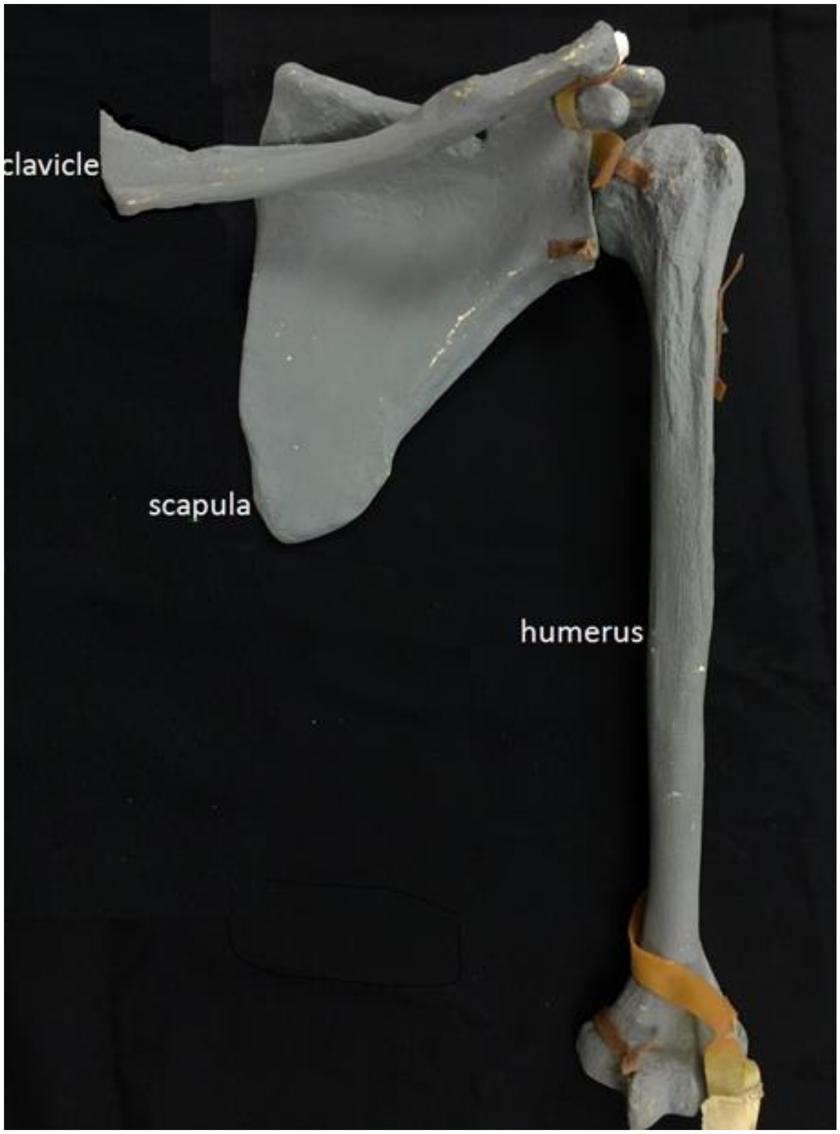

Figure 1-1: Bones of the shoulder complex

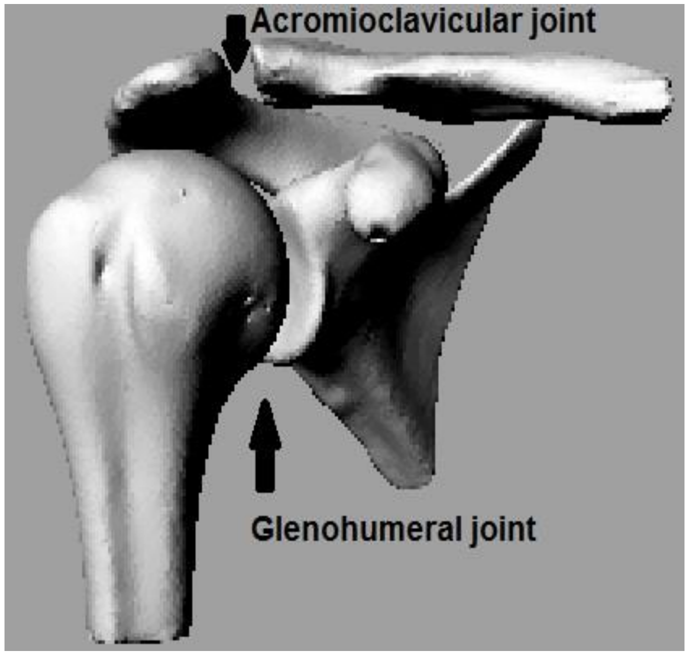

Figure 1-2: Joints of the scapula

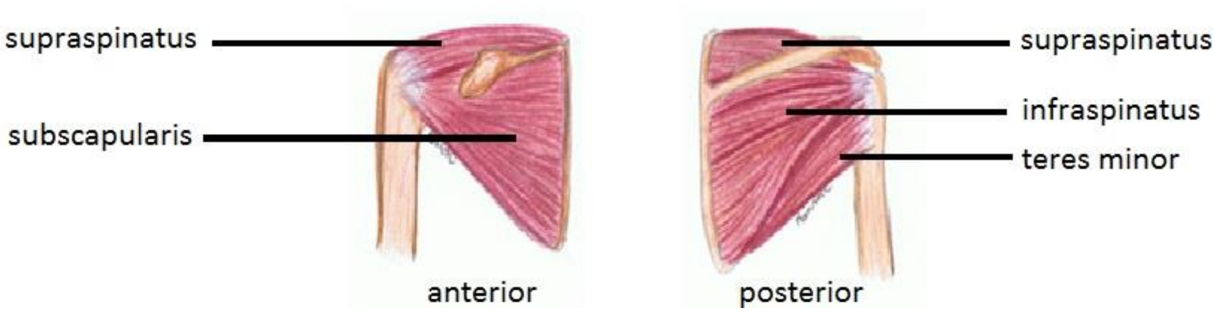

Figure 1-3: Muscles of the rotator cuff

1.3.2 Motion

The glenohumeral joint is classified as a ball and socket joint. A characteristic of this joint classification is that it has more degrees of freedom than any other joint type within the body. This joint is able to move with 6 degrees of freedom to produce the rotations of flexion, extension, abduction, adduction, internal and external rotation, as well as arm circumduction, illustrated in Figure 1-4 (Inman et al., 1944, Tortora, 2002). The humerus is also able to translate medio-laterally, anterio-posteriorly, and superio-inferiorly in relation to the scapula.

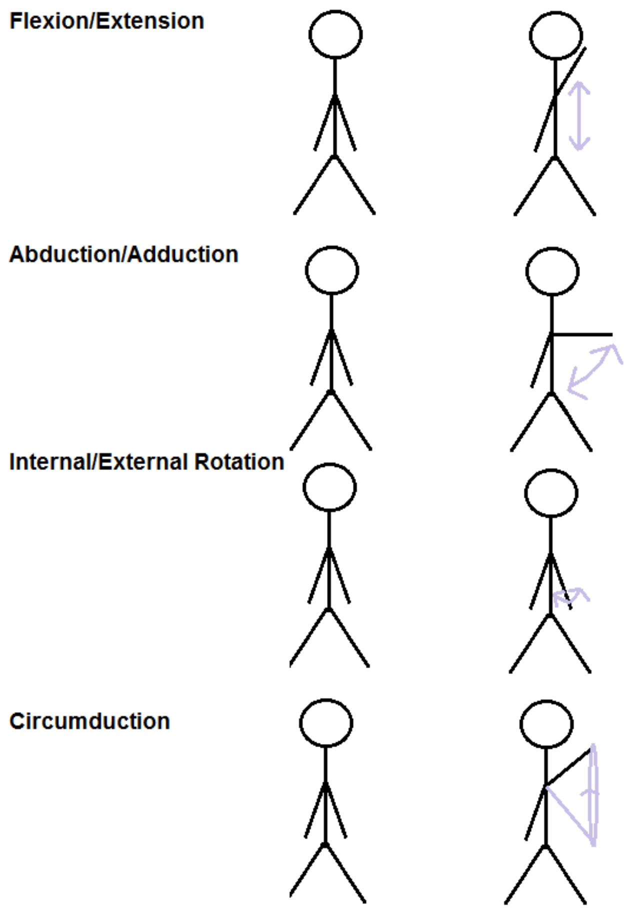

Figure 1-4: Motions at the scapulohumeral joint

Elevation of the arm at the glenohumeral joint in both flexion and abduction is accompanied by movement between the scapula and thorax. This additional joint movement increases the functional ability of the muscles performing the action (Inman et al., 1944). A position of stability of the scapula is achieved by oscillating of in relation to the humerus during the first 30-60° of elevation. Inman et al. (1944) observed that the scapula remains fixed, moves laterally, medially or oscillates until scapular stabilization at the glenohumeral joint is accomplished. This causes the early phase of motion to be highly irregular and it is unique for each individual (Inman et al., 1944). Inman et al. hypothesized that this irregular motion depends “upon the habitual position which the scapula occupies in the subject when at rest” (1944, pg 9).

One of the methods for describing the simultaneous motion of the joints of the shoulder complex is called scapulohumeral rhythm (SHR). SHR is defined as a ratio between scapulohumeral elevation and upward scapulothoracic rotation, often reported as a ratio of 2:1 for individuals with healthy shoulders (Inman et al., 1944, Giphart et al., 2013). Although Inman first described SHR as a single plane motion of upward and downward rotation. Currently, it also includes anterio-posterior tipping and internal and external rotation (Borstad and Ludewig, 2002). Although there have not been many studies of glenohumeral motion in-vivo until recently, the use of dynamic biplanar fluoroscopy is a main method for making such measurements.

Nishinaka et al. (2008) reported that 3D movement within the shoulder complex can be measured using biplanar fluoroscopy with an error of 0.5 mm. During this study, subjects performed arm abduction with two fluoroscope units recording motion of the shoulder complex. Motions of the humerus and scapula were calculated in 6 degrees of freedom. During initial abduction, the humeral head moved an average of 1.7 mm from inferior toward the centre of the glenoid cavity. Once abduction of the arm was over 80°, the humeral head stayed centred within 1 mm of the centre of the glenoid (Nishinaka et al., 2008). Bey et al. (2011) studied arm abduction through biplanar radiography. Results of this study also indicate movement of the humeral head from the inferior to the centre of the glenoid as humeral abduction increases.

Giphart et al. (2013) used biplanar fluoroscopic RSA to measure SHR in abduction, forward flexion and scaption (scapular plane elevation) using 8 male subjects. The SHRs observed were 2.0 ± 0.4:1 for abduction, 1.1 ± 0.3:1 for forward flexion and 1.6 ± 0.5:1 for scaption. The measurement of excursion of the humeral head was 5.1 ± 1.1 mm for abduction, 3.6 ± 1.1 mm for flexion and 2.4 ± 0.6 mm for scaption. The amount of excursion reported during abduction in this study is more than what was presented by previous studies (Nishinaka et al., 2008, Giphart et al., 2013).

Studies using biplanar radiography and fluoroscopic techniques have consistently shown that variability in the motion of the humeral head decreased as the angle of abduction increased (Nishinaka et al., 2008, Bey et al., 2011). This conclusion may be a result of musclular compensation. It is possible that greater force produced by the surrounding muscles is needed to continue to abduct the arm, leading to a more muscle fibres being recruited, possibly leading to a more stable joint (Nishinaka et al., 2008).

Using a markerless biplanar fluoroscopic system to analyze scapulohumeral kinematics, Matsuki et al. (2012) observed arm abduction. During initial position to 105˚ of abduction, the humeral head translated superiorly 2.1 mm. After this point, the humeral head translated inferiorly an average of 0.9 mm for the rest of the motion. An average external rotation of the humerus was reported to be 14˚ from the starting position to 60˚ of abduction, and then internal rotation of an average of 9˚ until full abduction was reached (Matsuki et al., 2012).

A study by Massamini et al. (2011) compared the use of a markerless RSA methodology using a model instead of implanted titanium spheres in the scapula and humerus in-vivo. This study included the calculation of motion of a subject's scapula and humerus in 6 degrees of freedom during dynamic tasks. The average difference between the two techniques was 0.27 ± 0.19 mm and $0.46 \pm 0.36°$ for the motion of the humerus in relation to the scapula (Massamini et al., 2011).

1.3.3 Rotator cuff pathology

Disorders of the rotator cuff are the major cause of pain and dysfunction of the shoulder joint in individuals over 30 years old (Mell et al., 2005). Specifically, the supraspinatus muscle is prone to injury because of its location between the head of the humerus and acromion. These bones can compress the supraspinatus tendon during shoulder movement, causing an injured or torn muscle. This type of muscular injury may lead to pain and variable motion at the glenohumeral joint (Mahfouz, Nicholson, Komistek, Hovis and Cubo, 2005, Tortora, 2002, Inman et al., 1944). A partial or full-thickness tear of a muscle of the rotator cuff will likely result in abnormal kinematics at the scapulohumeral joint and SHR (Ludewig and Reynolds, 2009, Giphart et al., 2013, Pauly, Gerhardt, Chen, and Scheibel, 2010, Miller et al., 2005). Scapular kinematic differences between shoulders that have healthy and injured rotator cuff muscles can be seen below in Table 1-1.

Table 1-1: A comparison of scapular kinematics in shoulders with healthy and injured rotator cuffs (adapted from Ludewig and Reynolds, 2009)

Motion	Healthy	Injured
Primary motion	Rotation upward	Limited rotation upward
Secondary motion	Tilt posteriorly	Limited tilt posteriorly
Accessory	Variable internal/external rotation	Greater internal rotation

A decrease in subacromial space and decreased rhythm can indicate injury at the shoulder complex. The changes in scapulohumeral kinematics indicate there may be compensation during the movement to avoid symptoms of the injury (Giphart et al., 2013, Ludewig and Reynolds, 2009).

1.3.4 Rotator cuff repair

When a subject complains of pain relating to their rotator cuff, initially conservative, non-operative modalities are attempted to manage pain symptoms and improve shoulder function and motion (Krabak, Sugar, and McFarland, 2003). Some of these methodologies include anti-inflammatory medication, corticosteroid injections, physical therapy and re-education of the muscles affected. If the symptoms of rotator cuff pathology persist with conservative treatment, surgical intervention is the next step towards reducing pain and increasing muscle function (Krabak et al., 2003).

A surgery for repair of the rotator cuff can provide pain relief, increased functional ability and patient satisfaction (Pauly et al., 2010). There are many surgical repair methods for a rotator cuff tear and a surgeon will choose one based on size and shape of the tear. Although the open method is considered the gold standard, there is a drive to minimize morbidity and amount of dissection during surgery. Over time, the arthroscopic (less invasive) and mini-open methods have been developed. The mini-open technique has a combination of the best properties of both open and arthroscopic approaches (Ghodadra, 2009, Sauerbrey et al., 2005, Ammon, Nyland, Chang, Burden, and Caborn, 2007).

Additionally, there are recommendations for surgeons regarding choice of suture technique to secure the tear. These suture techniques are developed for optimal initial fixation strength and footprint reconstruction, the amount of reattachment between severed portions of the muscle (Gerber, Schneeberger, and Beck, 1994). Single-row suturing was the predominant technique for a long time; however, as techniques developed, the double-row arthroscopic tear repair is becoming more common. This new technique allows for faster healing of the muscle compared to the single-row approach. This could be due to better footprint reconstruction and initial repair strength (Tashjian et al., 2010, Pennington et al., 2010, Ghodadra, 2009).

1.4 Rationale

Further developing the knowledge of shoulder motion from the descriptions provided by Inman et al. (1944) is essential to better understand shoulder function, adaptations to structural damage, surgical intervention and recovery. In-vivo motion of the scapulohumeral joint will be quantified six degrees of freedom with a precise, minimally invasive technique. Using markerless, biplanar fluoroscopy will create insightful data that is helpful to clinicians making diagnoses and surgical decisions for rotator cuff repair.

Minimizing risks to patients is imperative in both research and in surgery. Validating a generic shoulder model of the CT scans for use with the biplane fluoroscope system reduces the amount of radiation exposure to the subjects.

Quantifying SHR using RSA for both healthy, younger and older adult groups will allow for comparison of scapulohumeral kinematics. In addition, an evaluation using the proposed RSA technique to measure scapulohumeral kinematics in an injured group and post-supraspinatus repair group will be key to understanding changes in kinematics at the scapulohumeral joint during injury and after repair.

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Chapter 2

2 Validation of a novel biplanar fluoroscopic RSA approach for measuring joint kinematics using a generic Sawbone® model compared to subject-specific CT scan models

Abstract

Markerless biplanar fluoroscopic RSA usually involves an initial subject-specific CT scan to define the 3D model of the bony anatomy. This approach has a number of limitations including the expense, scheduling and, most importantly, the relatively large radiation dose. Alternative approaches that do not require a CT scan would reduce the radiation exposure to subjects participating in biplanar fluoroscopic RSA. This study compares the use of two different models based methodologies for measuring rotations and translations of the scapulohumeral joint during markerless biplanar fluoroscopic RSA. A novel approach uses a generic Sawbone® model and the traditional methodology used subject specific models developed from CT scans, similarly to previous research. Three healthy, normal subjects were recruited and underwent a CT scan and biplanar fluoroscopic data collection of the right scapulohumeral joint during abduction and forward flexion. Data at each 10% of motion for each subject were digitized in a virtual 3D environment using a RSA technique. Average differences in angles and translations between the two different model based methodologies were calculated. Statistical significance of these differences was measured using paired samples t-tests. No significant differences in angles and translations between generic and subject specific techniques were found. Based on the results of this study, generic shoulder models should be used instead of subject specific models for biplanar fluoroscopic RSA to minimize radiation exposure to the subject.

2.1 Introduction

Markerless biplanar fluoroscopic RSA has been successful in measuring movement of the scapulohumeral joint. Bey, Peltz, Ciarelli, Kline, and Divine (2011) used markerless biplanar fluoroscopic RSA to measure in-vivo shoulder function after rotator cuff repair surgery. This study compared scapulohumeral kinematics during abduction between repaired scapulohumeral joints and the healthy contralateral side. Contact centre at the glenohumeral joint was positioned significantly more anterior at 2 years post-surgery compared with a control group. A significantly larger superior contact path during abduction was observed in the 2 year post-surgery group compared with their contralateral shoulder and control group. This methodology relies on models created through subject-specific (SS) CT images (Bey, et al., 2011).

A major concern with biplanar fluoroscopic RSA is that each subject is exposed to radiation to create their SS CT image and during their fluoroscopy data capture session. Fox et al. (2011) created a protocol to reduce the amount of radiation exposure to the subject during the CT scan by 98% compared to the radiation from a standard CT scan. They determined that the radiation dosage can be as low as 0.75 mGy per slice, while total radiation exposure for the sequence can be minimized to 17 mGy create 3D models for accurate RSA (Fox et al., 2011). To obtain an optical density of 1.0, Bushberg, Seibert, Leidholdt, & Boone (2002) indicated that standard fluoroscopy uses approximately between 1 to 5 μR per frame, which is several thousandths less than the radiation required for even the low dose CT for markerless biplanar fluoroscopic RSA proposed by Fox (2011). Depending on the data required to be collected, the density of the individual subjects tissues in the area of interest and length of time the subject undergoes the fluoroscopy will increase the amount of radiation to which the subjects are exposed.

Alternative approaches have been developed that do not depend on subject specific CT imaging. For example, Hanson, Suggs, Freilberg, Durbhakula, & Li (2006) used a CAD model of total knee arthroplasty components rather than CT imaging. They used markerless biplanar fluoroscopic RSA to obtain knee kinematics in subjects with knee replacements. They obtained results with a small amount of error, $0.24 \pm 0.48°$ for rotations and 0.11 ± 0.11 mm for translations.

2.1.1 Rationale

Validating an alternative methodology of markerless biplanar fluoroscopy using a generic model will omit the reliance on a SS model. By not depending on a SS model, subjects will not need to undergo a CT scan of their humerus and scapula which will reduce the radiation exposure to the subject.

The purpose of this study was to compare the glenohumeral joint kinematic measurements obtained through RSA using SS humerus and scapula models to those of a generic Sawbone® (SB) model (Pacific Research Laboratories Inc., Vashon, WA). The null hypotheses are that statistically significant differences will be found with all six degrees of freedom, and the alternative hypothesis is that there will be no statistically significant difference between the models used for matching.

2.2 Methods

2.2.1 Participants

This study was approved by the University of Western Ontario's Research Ethics Board (certificate #15278) and all participants provided informed consent before data collection. Three healthy subjects with an average age of 30, (1 male, 2 female) with no history of shoulder dysfunction and no regular use of analgesia participated in data collection. Exclusion criteria included pregnant or nursing women, radiation workers, if a subject underwent two or more high-exposure radiological procedures in the past year, previous shoulder or arm surgery, or neurological dysfunctions.

2.2.2 Data collection

All subjects underwent a CT (Lightspeed VCT, GE Healthcare, Piscataway, NJ) scan of their right shoulder (10 mA current, 120 kV voltage, 0.8s scan time, 0.625 mm slice thickness) at University Hospital Campus, London Health Sciences Centre, London, Ontario, based on the parameters recommended by Allen (2011). The superior two thirds of the scapula, in addition to the top and bottom thirds of the humerus were captured in the SS CT scan images. The CT scan for the SB model was previously captured by Kedgley (2009); the entire scapula and humerus were scanned using 200 mA current, 140 kV voltage, 1 s scan time and 0.625 mm sections.

Participants attended a biplanar fluoroscopy data collection session in the Wolf Orthopedic Quantitative Imaging Laboratory (WOQIL) at the University of Western Ontario, London, Ontario. These sessions were conducted by John Henry (MRT), a trained radiography technician. Prior to data capture for each testing session, images were taken of the distortion grid placed on each image intensifier. This grid, created by Kedgley (2009), contained 131 tantalum beads at known 2D coordinates.

The fluoroscopes were positioned to create a capture volume for the data collection of fluoroscopic video. The capture volume was unique for each individual in order to best-capture the glenohumeral joint. Generally, one fluoroscope was positioned with the x-ray source anterio-superiorly towards the glenohumeral joint and the second fluoroscope x-ray source was positioned anterio-medially (Figure 2-1).

A calibration frame created by Kedgley (2009, Kedgley and Jenkyn, 2009) was made of a fiducial and control plane for each fluoroscope containing tantalum beads implanted into 9.5 mm acrylic sheets at known 3D coordinates relative to one location on the frame. There were 45 fiducial and 45 control points for each fluoroscope calibration, which allowed for a common, global coordinate system to be calculated. The calibration frame was placed within the capture volume ensuring that the fiducial points were closest to the image intensifier of the fluoroscope. Once positioned, images were taken of the calibration frame in the capture volume by both of the fluoroscopes, ensuring that one set of fiducial and control points could be seen by each fluoroscope (Figure 2-2).

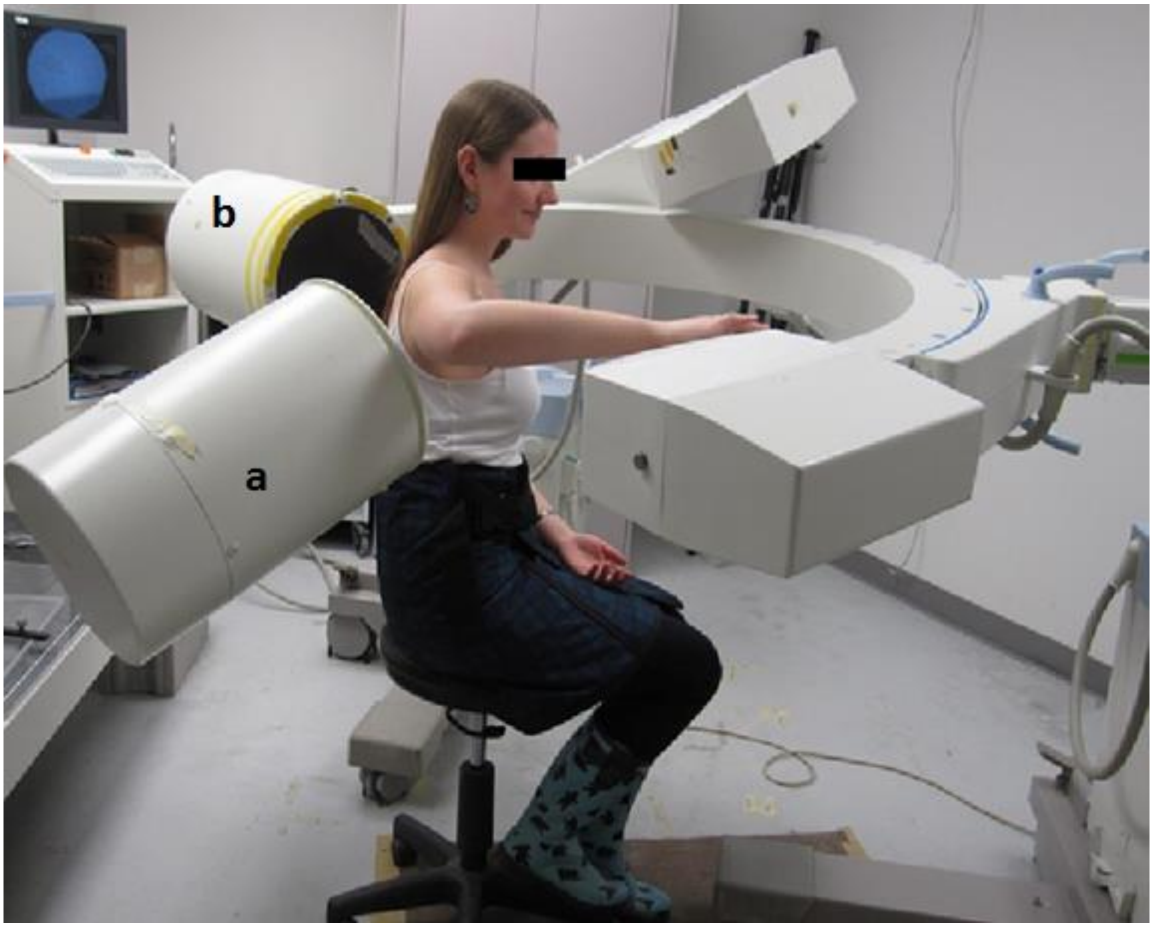

Figure 2-1: Laboratory experimental set-up with subject performing abduction. Two c-arm fluoroscopes are positioned in the laboratory environment to collect images of shoulder motion, one is angled superio-inferiorly from a lateral perspective of the joint

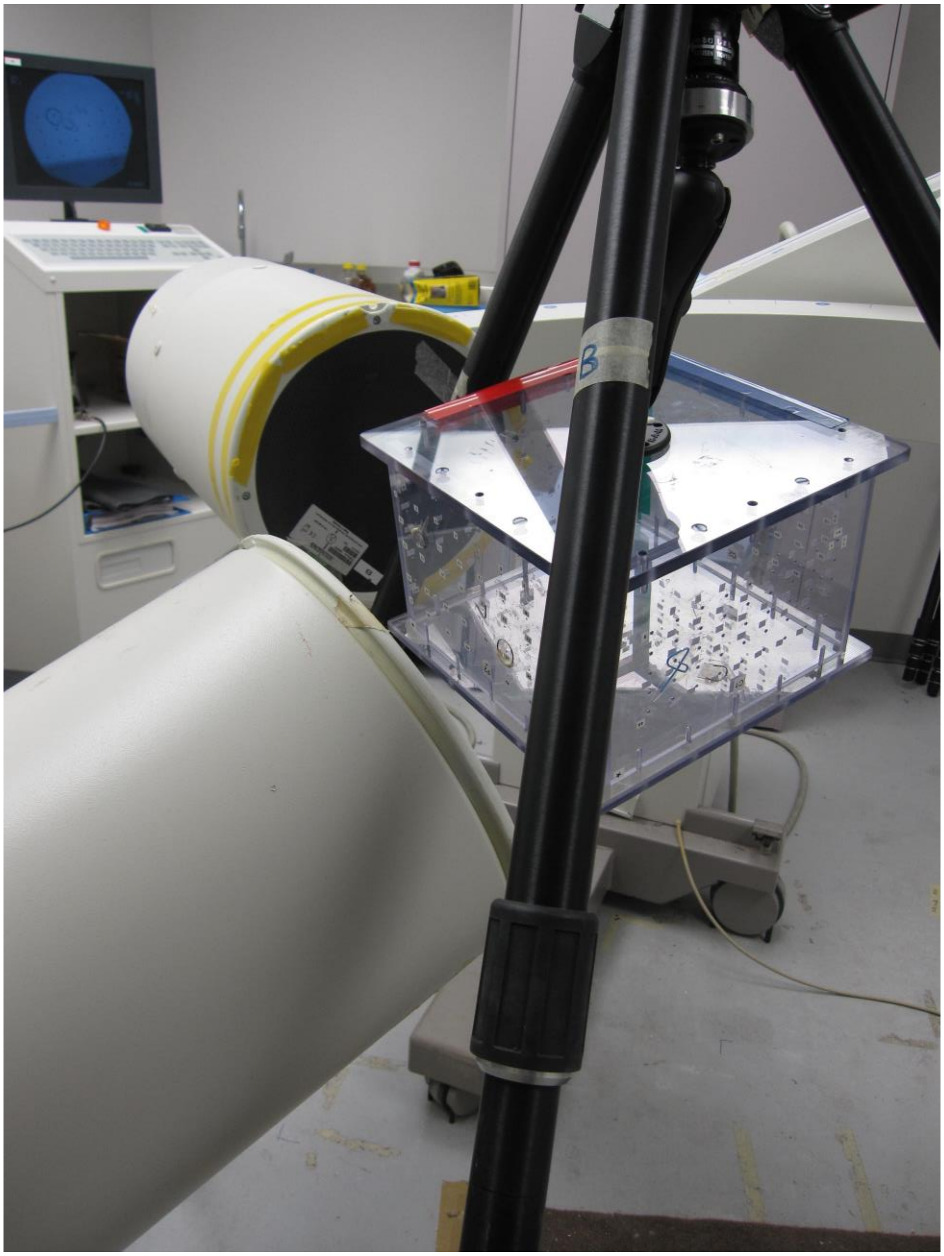

Figure 2-2: Calibration frame within the capture volume of the two fluoroscopes. The global coordinate system is presented on the calibration frame with the red (x), green (y), and blue (z) axes.

Subjects wore a sleeveless top and draped their pelvis in a lead skirt. Subjects sat on a stool while performing abduction (ABD) and forward flexion (FF) up to approximately 90° of humeral elevation from the ground. The technician recorded images of the scapulohumeral joint during these actions through the two fluoroscopes. The researcher instructed the subject to perform the movements slowly. The images of the scapulohumeral joint during the actions of ABD and FF using two convergent fluoroscopes (30 Hz, SIREMOBIL Compact L; Siemens AG Medical Solutions, Erlangen, Germany). The subjects were asked to perform the actions at a slow pace.

The subjects started with their body facing forward, their right elbow flexed to 90°, their upper arm touching the side of their body (torso) with neutral internal/external rotation. For the ABD motion, the subjects abducted their upper arm from this starting position until their upper arm reached the level of their shoulder (approximately 90° humeral elevation from the starting position). For the FF motion, subjects began from the starting position and flexed their shoulder until their upper arm reached the level of their shoulder (approximately 90° humeral elevation from the starting position).

2.2.3 Processing

The CTs were processed in open source DICOM viewing software (OsiriX, Pixmeo, Geneva, Switzerland). Using this software, SS and SB 3D models were created. The SB humerus model was imported into Rhinoceros® to connect the superior and inferior thirds of the SS humerus; the SS humerus pieces were manually superimposed onto the SB humerus and aligned based on the landmarks of the head, greater and lesser tubercles, medial and lateral epicondyles and the capitulum of the humerus. Once aligned, the SB model was deleted, leaving the two SS humeral pieces. These two pieces were linked using a meshing program within the software. The mesh was extended around the outer border of the inferior portion of the superior third of the humerus and extended down toward the outer border of the superior portion of the inferior third of the humerus. The SB model did not require any additional processing since the entire humerus was scanned.

Video data from the fluoroscopes was visually reviewed to determine the frames corresponding to the initial motion and the end of the motion using Adobe® Premiere® Pro (Adobe Systems, Inc., CS5.5.2). Data was trimmed to these time points. The length of the trial was determined from the frame count of each trial, and the frame number for each 10% of motion was identified. The images of the calibration frame, distortion correction device, starting position frame, and each 10% of trial time from the recorded data of each fluoroscope were extracted into tif format images.

The distortion grid tif image was imported into MATLAB® (2008b) and using custom code, locations of the tantalum beads were manually digitized with a computer mouse using weighted pixel values. This technique measured the darkest pixel of each point digitized, and created local 2D coordinates for each pixel. A fourth order polynomial equation was used to relate the x and y coordinates of each digitized bead to the known bead coordinates. This equation was then applied to all of the other frames of data from the corresponding fluoroscope. This process was repeated to similarly correct the distortion for the second fluoroscope images.

The calibration technique developed by Kedgley (2009, Kedgley and Jenkyn 2009) was used to determine the global laboratory coordinates, and parameters needed for analysis. The calibration frame tif image from each fluoroscope was imported into MATLAB®, and each of the fiducial and control points were digitized to create 2D coordinates for each point on the image based on a local coordinate system. The 2D points from the fiducial plane were used to determine 2D transformations between the image coordinate system of the fluoroscope and the global, laboratory coordinate system. The 2D points from the fiducial and control planes were used to determine the location of the foci of the x-ray source. These values were used as parameters to create a 3D virtual environment using Rhinoceros® (Robert McNeel & Associates, Seattle, WA) based on the locations of the x-ray sources and foci of the fluoroscopes in relation to the calibration frame coordinate system.

Once the virtual laboratory was created, the images from the fluoroscopes were imported onto their corresponding virtual fluoroscope image intensifiers and the SB model for the respective testing session was imported into the environment (Figure 2-3). A manual matching technique using an imbedded nudge tool allowing for translational increments as small as 0.1mm and rotational tool with increments of as small as 0.1° was employed to match the landmarks on the SS with the landmarks in the images created by the fluoroscopes. These landmarks included the greater and lesser tubercles of the humerus, humeral head, coracoid process, acromion and superior border of the spine of the scapula (Allen, 2011). Once the models were matched, additional landmarks to create coordinate systems of the scapula and humerus were identified on the 3D models using Kedgley and Dunning's (2010) scapular and humeral landmarks. These landmarks included the coracoid process (CP), acromial angle (AA), root of the scapular spine (TS), centre of the glenohumeral rotation centre (GH), medial and lateral epicondyles (ME, LE) (Figure 2- 4). The 3D coordinates of each of Kedgley and Dunning's (2010) landmarks were exported into an xls file for further analysis with custom MATLAB® code. This process was repeated for each of the ten fluoroscopy images for both the SS and SB models, for all participants.

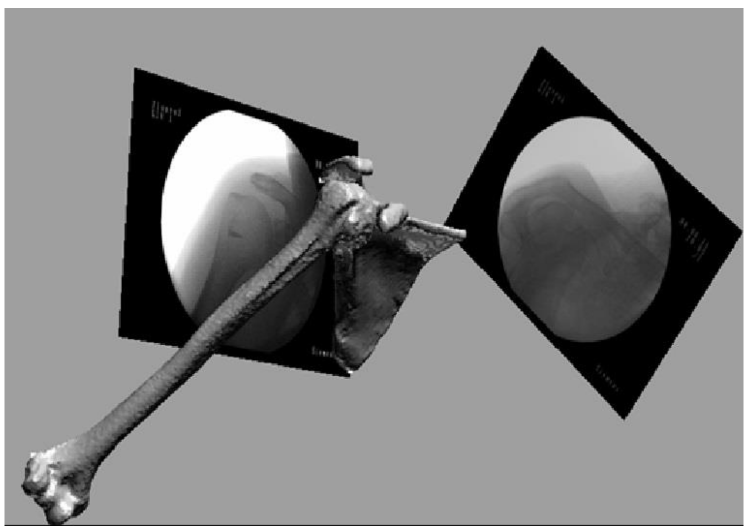

Figure 2-3: An example of the virtual laboratory set-up with Sawbone ® model. Each virtual image grid location is based on the location of the focus of the x-rays and the distance from the x-ray source. A 3D model is imported into this environment and is manually matched to a position that matches with landmarks present in the images from the fluoroscope.

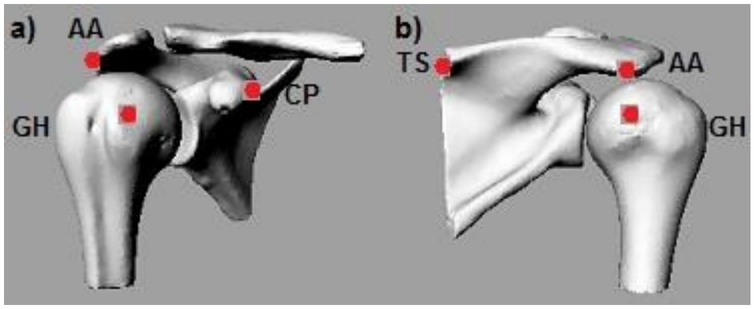

Figure 2-4: Landmarks on the humerus and scapula as viewed from both a) anterior and b) posterior views. These landmarks were used to determine the coordinate systems of the humerus and scapula. The naming convention for the landmarks is described in the body of the manuscript.

The exported landmark data were used to calculate the shoulder joint kinematics. Initially local scapular and humeral coordinate systems were defined. The scapular coordinate system was calculated according to Kedgley and Duning (2010) (Figure 2-5). The origin of the scapula was coincident with the AA landmark. The z axis was created as a vector from TS to AA. A second vector was between CP and AA. The y axis was calculated as the cross-product between the z axis and this second vector. The cross-product of the y axis and z axis was then used to define the x axis. The humeral coordinate system used was recommended by the International Society of Biomechanics (ISB) (Wu et al., 2005). The origin was defined as the location of the GH landmark. The y axis was formed by creating a vector joining the midpoint of the line between ME and LE to the GH landmark. The x axis was defined as the line perpendicular to the plane created between ME, LE and GH, facing forward. The z axis was cross-product of the y axis and x axis.

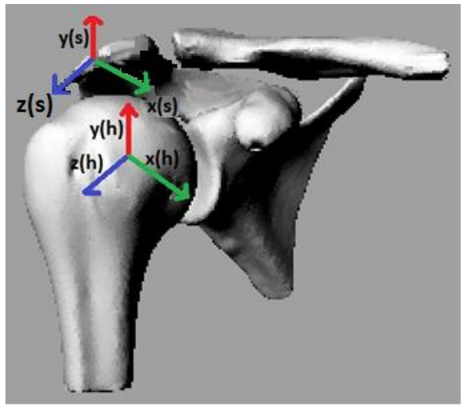

Figure 2-5: Coordinate systems for the scapula (s) and humerus (h), x axes (green), y axes (red) and z axes (blue) based on Kedgley and Denning (2010). The view of the scapulohumeral joint is anterio-medial.

Scapulohumeral rotations were calculated from the orientation of the humeral coordinate system in relation to the scapular coordinate system, using a Y-X-Y Euler angle sequence using custom MATLAB® code (Kedgley, 2009). Translations were calculated based on the location of the origin of the humeral coordinate system origin relative to the scapular coordinate system, as recommended by the ISB (Wu et al., 2005). These kinematic parameters were calculated for each video fluoroscopy frame (each 10% of each motion). The differences in the rotations and translations between the SS and SB models were calculated at each frame. The results of these differences were pooled into SB and SS groups for each rotation and translation.

2.2.4 Statistics

The strength of the linear relationship between the kinematic parameters determined using the SS and SB models were calculated using Pearson product-moment correlations. Paired samples t-tests of all the pooled SS and SB matching technique samples for all rotation and translations were completed using SPSS ® (IBM, Statistics 23) for all ABD and FF trials combined. Significance was set at $\alpha < 0.05$.

2.3 Results

On average, there was a strong correspondence between the kinematic parameters determined using the SS and SB models; the correlations between the SS and SB models were very strong (all > 0.96 except for translation in z which was 0.80; Table 2-1, Figure 2-6. The results of the t-tests determined that there were no significant differences in measurements of motion when matching using a SS or SB bone model for biplanar fluoroscopic RSA (Table 2-1); however, the variability was high.

Table 2-1: Average differences, statistical significance and correlations between the SB and SS measurement techniques using markerless biplanar fluoroscopic RSA. The flexion and abduction data were pooled.

Difference (SB-SS)	Mean ± Standard Deviation	T-test α value	Correlation between SS and SB measures
Plane of Elevation (˚)	1.06 ± 4.73	0.87	0.99
Angle of Elevation (˚)	-0.45 ± 6.16	0.57	1.00
Int/Ext Rotation (˚)	-0.54 ± 7.15	0.59	1.00
Translation x (mm)	-1.13 ± 5.04	0.89	0.99
Translation y (mm)	0.81 ± 5.61	0.27	0.96
Translation z (mm)	-0.61 ± 4.86	0.36	0.80

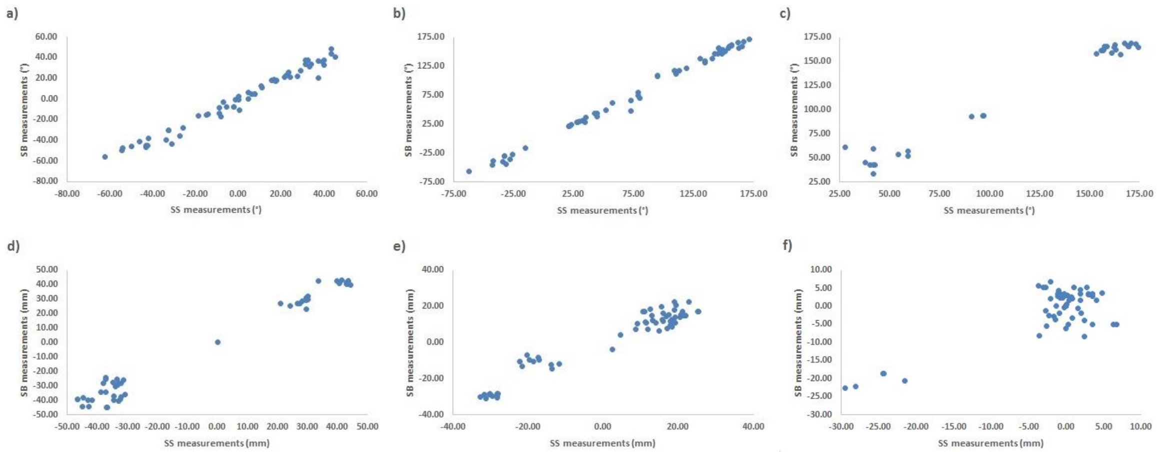

Figure 2-6: SS model measurements graphed with their corresponding SB measurements calculated for a) plane of abduction b) angle of abduction c) int/ext rotation d) translation in x e) translation in y and f) translation in z

2.4 Discussion

2.4.1 Comparisons of kinematics calculated between a SS model and SB model for matching

This study compared the scapulohumeral motions of healthy participants using subject-specific models and generic models based on a Sawbone® anatomical specimen. There was a strong concordance between parameters determined from the SS and SB models. These results indicate that markerless biplanar fluoroscopic RSA using a SB model does not lead to statistically significant differences compared to the typical approach using an SS model. Adopting the SB approach allows the researchers to reduce the subjects' radiation exposure because it omits the need for subjects to obtain a CT scan.

When Allen (2011) introduced a markerless biplanar fluoroscopic RSA method, differences between using a standard (beaded) biplanar fluoroscopic RSA methodology and markerless biplanar fluoroscopic RSA methodology ranged between 0.69˚ and 9.49˚

with standard deviation between 1.22˚ and 3.35˚. Allen (2011) collected data in-vitro in static positions, while the current study was performed in-vivo and motion captured was dynamic, which may account for the higher variance observed in the current study. Error was also introduced by using a generic shoulder model to match against the SS fluoroscopic data since the SB model represented average anatomy rather than each specific participant. Although differences between the two matching methodologies was not statistically significant, it compounded the existing error within markerless dynamic biplanar fluoroscopic RSA.

There was increased variability in the internal/external rotation average difference, which could indicate errors in the initial joint coordinate set up of the humerus SS and SB models. Wu et al. (2005) presented two options to create this coordinate system. The first option defined the distal end of the humerus y axis based on the ME and LE landmarks. However, the distance between the ME and LE is short, which may lead to increased error in the internal/external rotation angle as we have defined it. The second option is recommended to minimize this error, but was not possible in the current study because we could not obtain the necessary forearm landmarks.

A skin-based motion capture system, such as in the scapular kinematic study by Yano et al. (2010), indicated that the skin-motion artifact was between 1.2 ± 1.0 cm at the base of the scapular spine, 0.7 ± 0.6 cm for the acromial angle and 0.8 ± 1.0 cm for the coracoid process compared to radiographic data. These points and their variance are much greater than that found using the current method. Error in a skin-based marker motion capture data is higher than that found within the current study. The additional error inherent in the RSA calculations using the generic shoulder model is limited, while exposure to radiation from the CT scan is omitted using this new matching technique.

The results previously reported by Hanson et al. (2006) had less error than the current study. Their knee joint analysis used CAD models of knee implants that were implanted into individuals and the coordinate systems used for kinematic analysis were created based on the CAD model. The knee implant has distinct features to match with the fluoroscopic data while the humeral head is relatively featureless, possibly leading to larger errors in the current study. Additionally, the study by Hanson et al. (2006) requires implanting a device into the knee joint, which is very invasive, while the current study does not require any implantation for data analysis.

Kedgley, Shore, Athwal, Johnson & Faber (2013) evaluated shoulder kinematics in an in-vitro study and found no differences between scapulohumeral kinematics of the group with intact supraspinatus muscles and the group of shoulders with a 2 cm supraspinatus tear that was surgically repaired shoulders using an electromagnetic tracking device, however, we might expect to see different results in-vivo because of the complex nature of in vivo human movement.

2.4.2 Limitations

It is difficult to produce pure FF or ABD motion because of the interactions between the muscles and joints of the shoulder during motion (Heuberer, Kranzl, Laky, Anderl, & Wurnig, 2015). For this study, subjects were only verbally and visually guided to perform the motion, so the motions contained additional variability compared to studies that have provided tactile guidance and constraints through the motion. Isableu, Hanson, Rezzoug, Gorce & Pagano (2013) observed that the initial instruction given for motion can alter the kinematics on unconstrained 3D arm motion. The large variance in the standard deviations could also be due to a low sample size which reduces power of the statistical analysis (Faul, Erdfelder, Lang, & Buchner, 2007).

In the current in-vivo study, it is not possible to compare the results of the generic shoulder model RSA technique to the gold standard of markered biplanar fluoroscopic RSA. The markers must be embedded into the bone, which is very invasive, and not practical for individuals with healthy shoulder joints.

2.4.3 Recommendations

Radiation exposure to the subjects is a concern when using fluoroscopic RSA. Minimizing the radiation exposure decreases the risk to the subjects. Traditionally, RSA has required fluoroscopy and a CT scan at a standard clinical dosage (Kedgley, 2009, Allen, 2011). Fox et al., (2011) reduced the radiation dosage for the subjects by replacing the full dose CT scan with a low-dose scan. The next step to reducing radiation would be to omit the CT scan altogether. Although this has been achieved in specific patient populations, such as total knee joint replacements, using the 3D model of the joint implant (Hanson et al., 2006), it has not been performed in healthy normal subjects. The results from the current study indicate it is possible to use a SB model instead of and SS model, and that the differences in kinematics between subject specific models and the Sawbone® model were smaller than the errors in skin-mounted approaches.

In order for this technique to be globally accepted, more studies comparing generic and subject specific models for markerless biplanar fluoroscopic RSA should be completed. These findings are based on the shoulder joint and heavily depend upon parameters related to the complexity of the bones. Accordingly these studies should be repeated for other joints of the body.

2.5 Conclusion

A novel approach to markerless biplanar fluoroscopic RSA has been described in this chapter. The results of this study indicate that there is no significant difference when substituting a generic SB model for SS model during the registration technique for markerless biplanar fluoroscopic RSA. The use of a SB model will reduce radiation exposure to the subject can be by omitting the need for a SS CT scan and a SB model should substituted for SS model where possible.

2.6 References

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Chapter 3

3 Scapulohumeral motion: An age-based comparison

This study describes 3D scapulohumeral movement during abduction, forward flexion and a compound motion of arm across the chest. This study also contrasts the motion at the scapulohumeral joint of a healthy, younger group to that of a healthy, older group.

Abstract

Limited research has described age-related differences in scapulohumeral motion. Differences between the relationships of the scapula and humerus can be observed without the interference of soft-tissue when using a markerless biplanar fluoroscopic radiostereometric analysis technique to measure scapulohumeral kinematics. This technique provides more accurate information on bone motion than skin-based motion capture systems and minimizes invasiveness compared to traditional biplanar fluoroscopic radiostereometric analysis. Observing and describing healthy scapulohumeral motion is key to understanding the effects of aging on scapulohumeral joint function. A high prevalence of individuals with rotator cuff impairment is well documented and may cause differences in scapulohumeral kinematics when compared with a younger age group. Changes in range of motion may affect kinematics as an individual ages. This study employed the markerless biplanar fluoroscopic radiostereometric analysis technique using a generic shoulder model that was validated in the previous chapter. Participants included six healthy younger subjects (19-22 years old) and four healthy older subjects (50-52 years old). Subjects performed motion in three conditions, shoulder abduction, forward flexion and a compound motion of shoulder flexion, adduction and internal rotation in which they moved their right hand to the left shoulder (AAC). Six degrees of freedom of motion of the scapulohumeral joint was analyzed for frames extracted from each 10% of motion for these motions. A MANOVA was conducted to determine the statistical significance of differences between the motions the younger versus the older age groups, and the different shoulder motions. Many significant differences between the younger and older subjects were found between

motion conditions. Limited differences were found in early scapular plane tilt and superio-inferior translations between groups. This finding is important because it determines that older, healthy group should be used as a control group compared to groups with diagnosed rotator cuff impairment.

3.1 Introduction

It is important to observe scapulohumeral joint motion in a healthy, normal population is before observing the scapulohumeral joint motion of subjects with shoulder impairment. In addition to a healthy normal group, and older population with healthy, normal shoulders should be considered. Age significantly affects range of motion in all actions (Hwang and Jung, 2015, Barnes, Van Steyn, and Fischer, 2001). One of the reasons for this occurring is injury to the joint. After the age of 50 approximately 50% of individuals have some level of damage at the scapulohumeral joint such as bursitis or a partial or full thickness tear of the rotator cuff, likely due to some of the aforementioned reasons (Milgrom, Schaffler, Gilbert, and Van Holsbeeck, 1995). It is estimated that almost 60% of people over the age of 65 have a rotator cuff tear; this can limit shoulder function and increase pain in affected people of this age group, as well as increase medical care costs for treatment (Milgrom et al., 1995, Bey, Pelz, Ciarelli, Kline, and Devine, 2011).

3.1.1 Rationale

Markerless biplanar fluoroscopic radiostereometric analysis (RSA) has been successfully used to measure movement at the scapulohumeral joint (Allen, 2011). Determining a baseline measure for scapulohumeral joint motion in six degrees of freedom this accurate, in-vivo methodology is important describing the underlying relationships between the humerus and scapula in healthy populations.

The null hypotheses are that there are no differences in the angles and translations of the humerus relative to the scapula for the motions of singular plane and combined motions, or based on age. Additionally, variability of the kinematics will be similar between motions and age groups. With regards to the amount of time to complete each action, the null hypothesis is that the time to full range of motion will be similar between the two age groups.

3.2 Methods

3.2.1 Participants

This study was approved by the University of Western Ontario's Research Ethics Board (certificate #15278) and all participants provided informed consent. A total of 10 subjects were recruited in two age groups. The young adult age group was comprised of six healthy subjects between the ages of 18 and 22 (average 20 years old, 3 male and 3 female). The older adult group was comprised of four healthy subjects between the ages of 50-52 (average 50 years old, 2 male and 2 female). None of the participants had any history of shoulder dysfunction and they did not regularly use analgesia. Exclusion criteria included pregnant or nursing women, radiation workers, two or more high-exposure radiological procedures in the past year, previous shoulder or arm surgery or neurological dysfunctions.

3.2.2 Data Collection

Participants attended a fluoroscopy data collection session in the Wolf Orthopedic Quantitative Imaging Laboratory (WOQIL) at the University of Western Ontario, London, Ontario. These sessions were conducted by a trained radiography technician. Subjects wore a sleeveless top, and bottoms of their choice, and were draped in a lead skirt. Subjects sat on a stool while performing shoulder abduction (ABD) and forward flexion (FF) up to approximately 90° of humeral elevation from the ground.

The subjects assumed a starting position with their body facing forward, their right elbow flexed to 90°, their upper arm touching the side of their body (torso) with neutral internal/external rotation. For the ABD motion, the subjects abducted the scapulohumeral joint from this starting position until their arm was at the level of their shoulder (approximately 90° humeral elevation from the starting position). For the FF motion, subjects began from the starting position and then rotated their right upper arm in the sagittal plane up to the level of their shoulder (approximately 90° humeral elevation from the starting position). For AAC, the subject assumes the starting position and performed a compound motion of shoulder flexion, adduction and internal rotation in which they moved their right hand and place it on their left shoulder.

The fluoroscopes were positioned to create a capture volume for the data collection of fluoroscopic video. The capture volume was unique for each individual in order to best-capture the scapulohumeral joint. Generally, one fluoroscope was positioned with the x-ray source anterio-superiorly towards the scapulohumeral joint and the second fluoroscope x-ray source was positioned anterio-medially. A technician recorded images of the scapulohumeral joint during these actions using two convergent fluoroscopes (30 Hz, SIREMOBIL Compact L; Siemens AG Medical Solutions, Erlangen, Germany). The subjects were asked to perform the actions at a slow pace.

Fluoroscopic images of the calibration frame, distortion correction device and trials of subjects performing ABD, FF and AAC were digitized into tif format using Adobe® Premiere® Pro (Adobe Systems, Inc., CS5.5.2). The calibration procedure from Chapter 2 was used to determine the unique parameters for the laboratory set-up in each data set. These values were used as parameters to create a 3D virtual environment based on the locations of the x-ray sources and foci of the fluoroscopes relative to the calibration frame (global) coordinate system using commercial software (Rhinoceros® 4.0, Robert McNeel & Associates, Seattle, WA).

Video data from the fluoroscopes was visually reviewed to determine the frame count from the initial motion until the end of the motion using Adobe® Premiere® Pro (Adobe Systems, Inc., CS5.5.2). Data was trimmed to these time points. Every 4th frame of data within these time points was imported into the 3D virtual environment for matching for each motion condition.

A CT scan of Sawbone® scapulohumeral model was previously collected and processed according to the procedure in Chapter 2. This model was then imported into the virtual environment and matched to corresponding fluoroscope image pairs from data collection.

A manual matching technique using an imbedded nudge tool allowing for translational increments as small as 0.1mm and rotational tool with increments of as small as 0.1° were employed to match the landmarks on the model with the landmarks in the images created by the fluoroscopes. These landmarks were the greater and lesser tubercles of the humerus, humeral head, coracoid process, acromion and superior border of the spine of the scapula (Allen, 2011).

Once the model was matched to the fluoroscope images, additional landmarks to create coordinate systems of the scapula and humerus were identified using the suggested ISB protocol for scapular and humeral coordinate systems (Wu, 2005). These landmarks include the inferior angle (AI), acromial angle (AA), root of the scapular spine (TS), centre of the scapulohumeral rotation centre (GH), medial and lateral epicondyles (ME, LE). The 3D laboratory coordinates of each of these landmarks were exported into an xls file for further processing in a custom program in MATLAB® 2008b (Mathworks Inc., Natick, MA).

3.2.3 Processing

The scapular and humeral coordinate system was calculated according to Wu et al. (2005). The origin of the scapula was coincident with the AA landmark. The z axis was created as a vector from TS to AA, pointing towards AA. A perpendicular line from the plane formed by AI, AA, and TS, pointing forward was created to form the x axis. The y axis was calculated as the cross-product between the x and z axes. The humeral coordinate system used was recommended by the International Society of Biomechanics (ISB) (Wu et al., 2005). The origin was defined as the location of the GH landmark. The y axis was formed by creating a vector joining the midpoint of the line between ME and LE to the GH landmark. The x axis was defined as the line perpendicular to the plane created between ME, LE and GH, facing forward. The z axis was cross-product of the y axis and x axis.

Scapulohumeral rotations were calculated from the orientation of the humeral coordinate system in relation to the scapular coordinate system, using a Y-X-Y Euler angle sequence using a custom MATLAB® (Kedgley, 2009). Translations were calculated based on the location of the origin of the humeral coordinate system origin to the scapular coordinate system origin based on the axes of the scapula, based on recommendations by the ISB (Wu et al., 2005). These kinematic parameters were calculated for every 4th video fluoroscopy frame for every trial. A qualitative comparison of possible data reduction curves was completed in an incremental fashion compared to the intact curve. It was observed that the peaks, troughs, and features of the curves was best preserved using every 4th data point. These kinematic parameters were then normalized to 100%, in order to compare them between subjects.

Rotations are based on the location of the origin of the humerus local body coordinate system relative to the scapular coordinate system. The x rotation corresponds to abduction (+)/adduction (-), y direction corresponds to external (+)/internal (-) rotation and the z direction corresponds to anterior (+)/posterior (-) tilt (Figures 3-1 to 3-3).

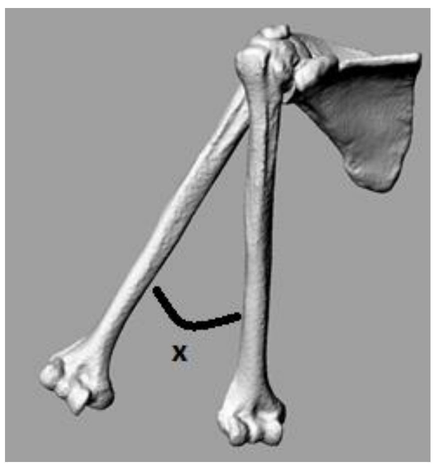

Figure 3-1: Rotation about the x axis of the scapula reflecting the abduction angle. Adduction is motion in the opposite direction.

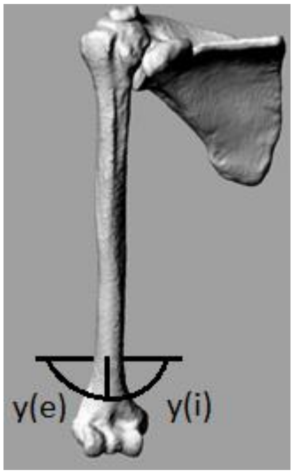

Figure 3-2: Rotation about the y axis of the scapula reflecting the internal y(i) and external y(e) angle. External rotation is positive rotation, internal rotation is negative rotation.

Figure 3-3: Rotation about the z axis of the scapula reflecting the anterior tilt angle. Posterior tilt is motion in the opposite direction.

Translations are based on the location of the origin of the humerus local body coordinate system relative to the scapular coordinate system. The x direction corresponds to anterior (+)/posterior (-) direction, y direction corresponds to lateral (+)/medial (-) direction and the z direction corresponds to superior (+)/inferior (-) translation.

These data were filtered using a 6th order low-pass Butterworth filter with a cut-off frequency of 3 Hz. The kinematics were normalized to 100 points and ensemble averaged for each age group and condition (motion). Based on these time-normalized data points, the rotations and translations at each 10% of the motion were used for a statistical analysis.

3.2.4 Statistics

A multivariate analysis of variance (MANOVA) were calculated in SPSS ® (IBM, Statistics 23), where statistical significance was determined at $p < 0.05$. The MANOVA was a 2 × 69 × 3 independent samples analysis using three factors: group as a factor that consisted of two independent groups (younger and older), kinematics in six degrees of freedom at each 10% of the trial (60) and average overall variance of each of the kinematic variables (9), and motion condition (ABD, FF, or AAC). Tukey's Honestly Significant Difference tests were completed post-hoc to determine pairwise significant comparisons based on the results from the MANOVA. Root mean square error (RMSE) was calculated to compare the amount of difference in kinematics for the older group in relation to the younger group. This was calculated for the point at each 10% of motion for each condition. The average and standard deviations were calculated for the amount of time to peak motion for each of the two groups for each motion. Independent samples t-tests with significance set at $\alpha < 0.05$ were used to determine if there were statistically significant differences between the younger and older groups.

3.3 Results

Scapulohumeral kinematics were similar for both groups over the three motion conditions. Main effects were observed by group (younger, older) at 10% and 20% of motion for superio-inferior translation and the average variability of internal/external rotation, and by condition (ABD,FF, AAC) for angular tilt, internal/external rotation, medio-lateral translation, anterio-posterior translation, superio-inferior translation, and the average variability during rotation, anterio-posterior translation and superio-inferior translation (Figures 3-4, 3-5, Tables 3-1, 3-5). An interaction effect was observed at 10% of motion in angular tilt.

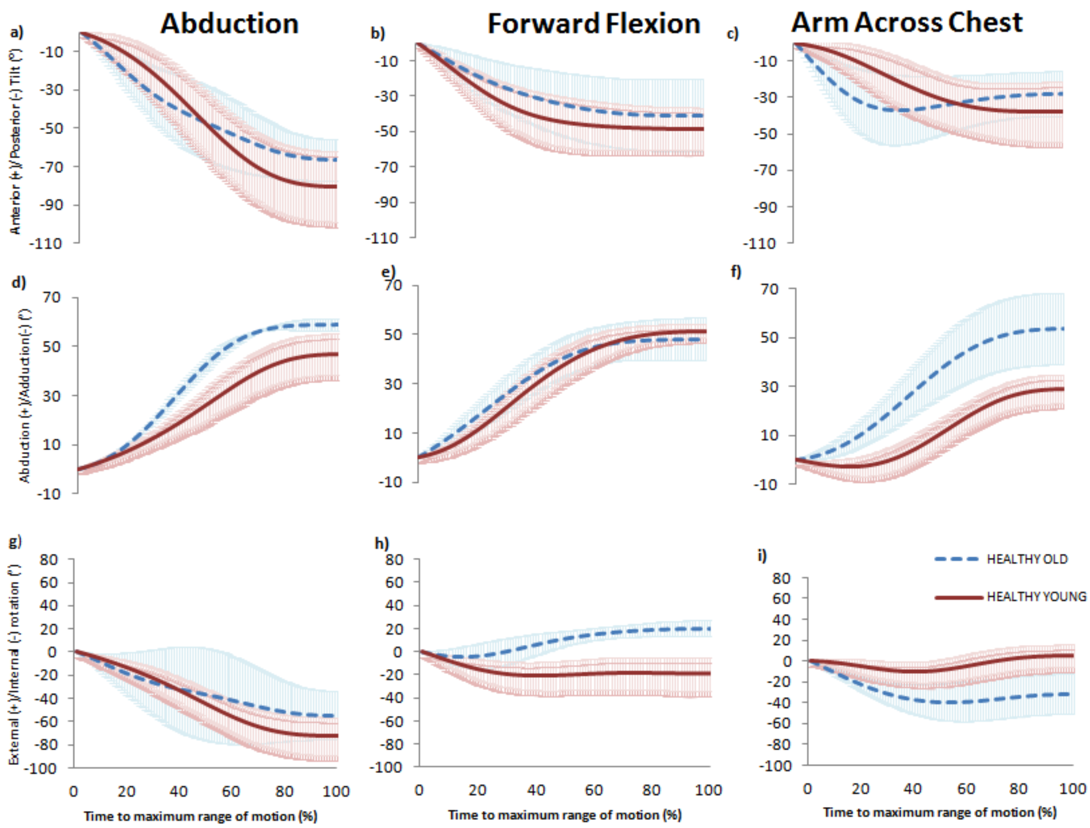

Figure 3-4: Mean rotations (line) and standard error of measurement (shading) during ABD (a,d,g), FF (b,e,h), and AAC (c,f,i). The healthy younger subjects are shown in red and the healthy older subjects are shown in blue.

Posterior tilt was significantly different in both groups during all three motion conditions (Figure 3-4). The largest change in scapulohumeral tilt was during ABD. The abduction angle increased in all three conditions as the amount of motion increased. ABD and FF had similar scapulohumeral motion for both age groups, however, there was more abduction in the older-aged group during the AAC trials. There was external rotation as ABD angle increased during the ABD trials. As the angle in FF increased, internal rotation was observed for the older aged group while external rotation was found in the younger age. During AAC trials, the younger population maintained neutral internal/external rotation through the entire motion while the older group had a trend of continuous external rotation throughout the motion.

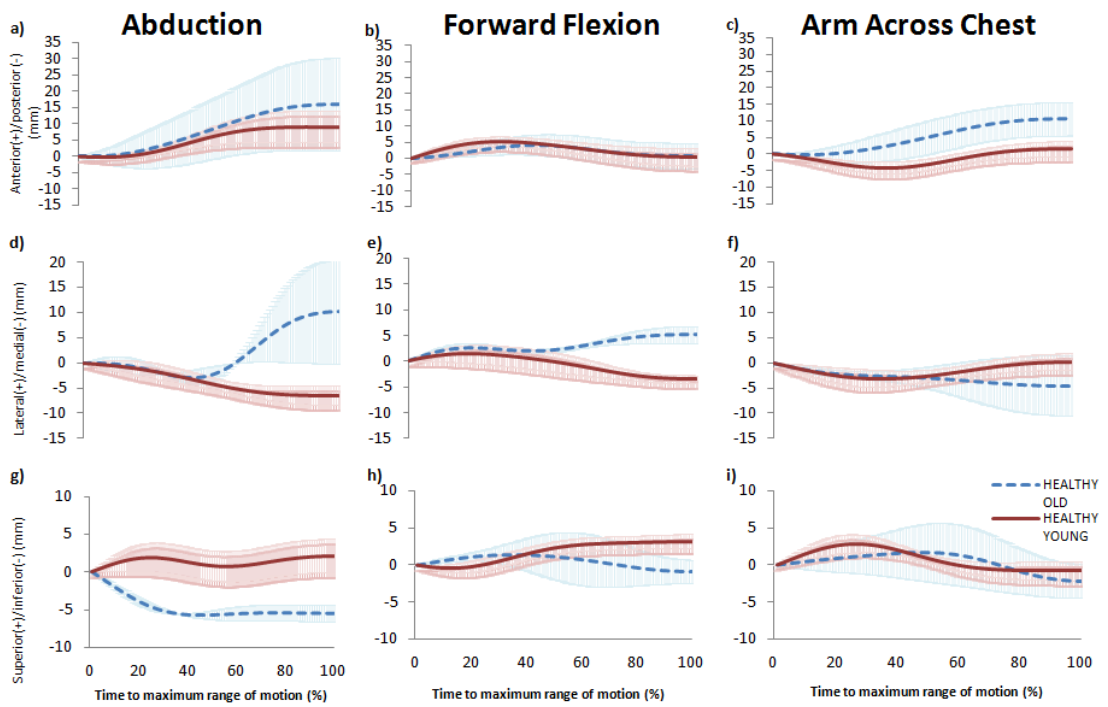

Figure 3-5: Mean translations (line) and standard error of measurement (shading) during ABD (a,d,g), FF (b,e,h), and AAC (c,f,i). The healthy younger subjects are shown in red and the healthy older subjects are shown in blue.

The largest translations were seen during ABD while smaller translations were noted in both groups for FF and AAC (Figure 3-5). Approximately 15 mm of anterior translation was seen in both groups during the ABD trials. During the FF trials, there was a small amount of anterior translation in the first 40% of motion, followed by posterior translation for the remainder of the FF motion. The shoulders of both groups moved similarly during the FF trials. During AAC, the younger group had a posterior translation of about 5 mm through the first 40% of motion, and then moves anteriorly until the end of the motion. The older group had an anterior translation of the humerus relative to the scapula throughout the entire motion, up to a maximum of approximately 10 mm from its original starting position.

Lateral translations were observed in ABD and FF trials in the younger group, while medial translation were observed in the older group during these conditions. The medio-lateral translations were within 7 mm for ABD, and 5 mm for FF and AAC in the younger population. Medial translations of the humerus in the older group were 10 mm in ABD and 5 mm in FF. During the AAC condition, the older group had a medial translation of their humeral head in relation to the scapula, the humeral heads of the younger group were similar until 50% of motion, where it moved laterally.

There was limited superior translation in the young group for all three conditions. During ABD, the younger group varies between superior and inferior translations, during FF there was an initial, small inferior translation followed by superior translation, and in AAC, there was an initial superior translation followed by inferior translation after about 30% of the motion. In the older group, during ABD, there was an inferior translation of 5 mm which was reached after 40% of motion. During FF and AAC the motion of the humeral head stays neutral for the older age group.

The appendix lists all of the descriptive statistics. The tables below present the results that are statistically significant. Table 3-1 illustrates the differences in scapular tilt, Table 3-2 notes the differences in internal/external rotation, and Tables 3-3, 3-4 and 3-5 show the differences for anterio-posterior, medio-lateral, and superio-inferior translations during motion, respectively.

Table 3-1: Average motion and standard deviation of anterior tilt angle between age groups (°). Statistically significant differences were noted between groups at 10% of motion and between motion conditions during early and late motion.

Percentage of motion (%)	Motion	Younger	Older
10 [a,c]	ABD	-5.45 ± 7.60	-11.51 ± 7.92
	FF[b]	-14.59 ± 13.65	-11.86 ±13.53
	AAC[b]	-5.91 ± 9.96	-7.68 ± 6.78
20	ABD	-13.48 ± 17.53	-23.81 ± 15.56
	FF[b]	-31.03 ± 25.38	-23.38 ± 22.10
	AAC[b]	-16.25 ± 20.88	-13.65 ± 11.29
70	ABD[b]	-57.91 ± 35.09	-59.71 ± 21.32
	FF	-62.39 ± 37.98	-50.40 ± 40.23
	AAC[b]	-39.41 ± 41.80	-19.86 ± 18.94
80	ABD[b]	-61.16 ± 32.58	-63.94 ± 17.66
	FF	-62.06 ± 37.27	-51.80 ± 40.70
	AAC[b]	-36.06 ± 44.98	-19.13 ± 18.41
90	ABD[b]	-62.42 ± 31.19	-66.12 ± 15.67
	FF	-61.87 ± 36.87	-52.45 ± 40.86
	AAC[b]	-34.03 ± 46.89	-19.39 ± 18.18
100	ABD[b]	-62.68 ± 30.79	-66.70 ± 15.11
	FF[b]	-47.74 ± 33.60	-52.62 ± 40.91
	AAC	-33.41 ± 47.49	-18.23 ± 18.40

Significant differences for age group (a), motion condition (b) and group*condition(c)

Table 3-2: Average motion and standard deviation of internal/external rotation between age groups (°). Statistically significant differences were noted between motion conditions during early and late motion.

Percentage of motion (%)	Motion	Younger	Older
10	ABD	-3.73 ± 4.86	-6.84 ± 8.40
	FF [b]	-6.99 ± 19.39	-5.07 ± 16.38
	AAC [b]	3.76 ±6.24	-9.94 ± 6.93
70	ABD [b]	-51.07 ± 28.79	-45.55 ± 47.44
	FF	-26.20 ± 52.49	17.97 ± 12.97
	AAC [b]	4.48 ± 22.59	-22.18 ± 32.69
80	ABD [b]	-54.15 ± 27.21	-50.37 ± 38.26
	FF	-25.81 ± 54.13	-18.13 ± 14.59
	AAC [b]	8.84 ± 20.17	-19.31 ± 31.42
90	ABD [b]	-55.19 ± 20.05	-53.37 ± 31.96
	FF	-25.70 ± 54.85	17.77 ± 14.80
	AAC [b]	11.18 ± 18.40	-17.45 ± 30.69

Significant differences for motion condition (b)

Table 3-3: Average motion and standard deviation of anterio-posterior translations between age groups (mm). Statistically significant differences were noted between motion conditions at every 10% of motion after 30%.

Percentage of motion (%)	Motion	Younger	Older
30	ABD [b]	3.14 ± 1.20	2.69 ± 8.95
	FF [b]	3.36 ± 4.44	1.47 ± 3.23
	AAC [b]	-4.91 ± 0.87	-2.00 ± 4.40
40	ABD [b]	4.98 ± 4.26	5.10 ± 11.04
	FF [b]	3.43 ± 4.42	1.71 ± 4.40
	AAC [b]	-5.14 ± 1.98	-1.48 ± 4.35
50	ABD [b]	6.68 ± 7.87	7.80 ± 12.72
	FF [b]	3.18 ± 4.40	1.28 ± 5.24
	AAC [b]	-3.83 ± 5.54	-0.20 ± 3.69
60	ABD [b]	8.01 ± 11.09	10.56 ± 14.52
	FF	2.93 ± 4.85	0.21 ± 5.57
	AAC [b]	-1.44 ± 2.46	1.63 ± 2.73
70	ABD [b]	8.95 ± 13.29	13.06 ± 16.34
	FF [b]	2.87 ± 5.78	-1.08 ± 5.46
	AAC	1.08 ± 2.21	3.50 ± 2.03
80	ABD [b]	9.52 ± 14.39	14.85 ± 18.56
	FF	2.92 ± 6.72	-2.05 ± 5.18
	AAC [b]	2.96 ± 2.14	4.84 ± 1.95
90	ABD [b]	9.73 ± 14.73	15.74 ± 19.68
	FF	2.99 ± 7.29	-2.50 ± 5.00
	AAC [b]	3.92 ± 2.23	5.49 ± 2.08
100	ABD [b]	9.79 ± 14.76	15.97 ± 20.00
	FF [b]	3.01 ± 7.47	-2.61 ± 4.96
	AAC	4.19 ± 2.28	5.65 ± 2.12

Significant differences for condition (b)

Table 3-4: Average motion and standard deviation of medio-lateral translations between age groups (mm). Statistically significant differences were noted between motion conditions from the initial 10% of motion until 60% of motion.

Percentage of motion (%)	Motion	Younger	Older
10	ABD	-0.63 ± 2.44	-0.08 ± 1.82
	FF [b]	0.73 ± 2.33	1.13 ± 0.80
	AAC [b]	-1.85 ± 2.67	-1.62 ± 0.85
20	ABD [b]	-1.68 ± 3.98	-0.71 ± 2.17
	FF [b]	0.70 ± 3.31	1.67 ± 1.30
	AAC [b]	-3.15± 4.70	-2.46 ± 1.38
30	ABD [b]	-2.22 ± 4.26	-1.86 ± 0.64
	FF [b]	-0.13 ± 2.68	1.76 ± 1.36
	AAC [b]	-3.50± 5.43	-2.67 ± 1.85
40	ABD [b]	-3.10 ± 3.52	-2.80 ± 1.58
	FF	-1.36 ± 1.11	1.86 ± 1.10
	AAC [b]	-2.98 ± 4.71	-2.34 ± 2.76
50	ABD [b]	-3.92 ± 2.38	-2.33 ± 2.21
	FF [b]	-2.49 ± 0.76	2.29 ± 0.81
	AAC [b]	-1.92 ± 3.07	-2.16 ± 4.52
60	ABD [b]	-4.62 ± 1.98	0.25 ± 0.41
	FF [b]	-3.17 ± 1.82	2.95 ± 1.78
	AAC [b]	-0.60 ± 1.49	-2.12 ± 7.15

Significant differences for condition (b)

Table 3-5: Average motion and standard deviation of superio-inferior translations between age groups (mm). Statistically significant differences were noted between age groups for all conditions and between motion conditions in early motion (10-20%).

Percentage of motion (%)	Motion	Young	Old
10 [a]	ABD [b]	0.35 ± 1.35	-2.14 ± 0.52
	FF [b]	-0.39 ± 0.94	0.42 ± 0.55
	AAC [b]	2.46 ± 2.38	-0.54 ± 0.92
20 [a]	ABD	0.71 ± 2.62	-4.17 ± 0.63
	FF	-0.43 ± 1.25	1.40 ± 1.32
	AAC	3.86 ± 3.53	-0.65 ± 2.48

Significant differences for group (a), condition (b)

Variability in the motion between all three conditions were statistically significant for internal/external rotation, anterio-posterior translation and medio-lateral rotation (Table 3-6).

Table 3-6: Average variability between younger and older age groups. Significant differences found in variability of motion between age groups for internal/external rotation and anterio-posterior and medio-lateral translations. Significant differences were also observed between all motion conditions.

Variable	Motion	Young	Old
Internal/external rotation[a]	ABD[b]	11.39 ± 4.41	31.50 ± 7.77
	FF[b]	11.47 ±3.77	7.12 ± 2.48
	AAC[b]	9.14 ± 4.40	13.99 ± 6.40
Anterio-posterior translation[a]	ABD[b]	2.64 ± 1.75	10.71 ± 3.01
	FF[b]	1.75 ± 0.65	2.80 ± 1.30
	AAC[b]	1.57 ± 0.88	3.89 ± 1.62
Medio-lateral translation[a]	ABD[b]	1.35 ± 0.43	5.09 ± 2.49
	FF[b]	1.35 ± 0.52	0.83 ± 0.45
	AAC[b]	1.30 ± 0.54	1.57 ± 2.10

Significant differences for group (a), condition (b)

RMSE values were most different in ABD trials between groups. As motion increase, there is an increase in the difference between the two groups for all rotations and translations (Table 3-7). During FF, as motion increased, differences between the two groups for external/internal rotation, lateral/medial and superior/inferior translations increased, and anterior/posterior translation decreased (Table 3-8). In AAC, as motion increased, the differences between the two groups for all rotations and translations increased except anterior/posterior tilt (Table 3-9).

Table 3-7: RMSE for the older group compared to a younger group during ABD. As motion increases, there is increased difference between the two groups for all rotations and translations.

Time of motion (%)	Rotations (°)			Translations (mm)		
	Anterior/ posterior tilt	Abduction/ adduction	External/ internal rotation	Anterior/ posterior	Lateral/ medial	Superior/ inferior
10	6.14	0.35	3.23	0.17	0.32	3.36
20	10.49	2.88	4.86	0.63	0.29	5.93
30	10.39	7.54	3.16	1.09	0.02	7.06
40	5.52	12.88	2.07	1.46	0.11	6.97
50	1.75	16.76	9.05	1.97	1.74	6.49
60	8.15	17.80	15.03	2.99	5.34	6.33
70	11.95	16.35	18.19	4.45	10.04	6.65
80	13.43	14.10	18.84	5.83	13.99	7.18
90	13.72	12.58	18.50	6.67	16.06	7.55
100	13.71	12.09	18.26	6.93	16.61	7.97

Table 3-8: RMSE for the older group compared to a younger group during FF. As motion increased, differences between the two groups for external/internal rotation, lateral/medial and superior/inferior translations increased, and anterior/posterior translation decreased.

Time of motion (%)	Rotations (°)			Translations (mm)		
	Anterior/ posterior tilt	Abduction/ adduction	External/ internal rotation	Anterior/ posterior	Lateral/ medial	Superior/ inferior
10	2.86	3.78	4.93	1.93	0.80	1.05
20	6.40	5.62	12.48	2.53	1.15	1.36
30	9.28	5.64	20.95	1.89	1.17	0.84
40	10.48	4.58	28.00	0.83	1.37	0.15
50	10.02	2.99	32.42	0.10	2.26	1.17
60	8.85	1.06	34.83	0.11	3.98	2.03
70	7.93	0.88	36.58	0.10	6.01	2.77
80	7.59	2.35	38.19	0.17	7.63	3.44
90	7.63	3.09	39.27	0.31	8.47	3.91
100	7.70	3.29	39.63	0.40	8.69	4.08

Table 3-9: RMSE for the older group compared to a younger group during AAC. As motion increased, differences between the two groups for all rotations and translations increased except anterior/posterior tilt.

Time of motion (%)	Rotations (°)			Translations (mm)		
	Anterior/ posterior tilt	Abduction/ adduction	External/ internal rotation	Anterior/ posterior	Lateral/ medial	Superior/ inferior
10	13.37	4.44	10.03	0.72	0.07	1.16
20	20.67	10.41	17.52	2.53	0.33	1.82
30	20.40	16.81	22.45	4.82	0.56	1.53
40	14.53	22.32	26.37	6.75	0.43	0.41
50	6.55	25.87	30.29	7.93	0.21	0.83
60	0.66	27.16	33.83	8.48	1.31	1.38
70	5.76	26.74	36.09	8.75	2.63	0.90
80	8.63	25.72	36.81	8.94	3.81	0.17
90	9.83	24.99	36.67	9.05	4.53	1.07
100	10.13	24.75	36.50	9.08	4.76	1.40

Three younger group took significantly less time than the older group to reach maximum motion during ABD, no other statistically significant differences were observed (Table 3-10).

Table 3-10: Average time to maximum motion (s) and standard deviations in age groups by condition. The younger age group took significantly less time to perform ABD than the older group.

Motion	Younger	Older
ABD[a]	1.1 ± 0.1	1.9 ± 0.4
FF	2.2 ± 0.8	2.1 ± 0.6
AAC	1.6 ± 0.4	2.2 ± 0.4

Significant differences for group (a)

3.4 Discussion

3.4.1 Comparisons between age groups

The kinematics between the groups were significantly different. The older group demonstrated increased internal rotation during AAC. This result, coupled with the observation that increased internal rotation is an indication of rotator cuff impairment (Ludewig and Reynolds, 2009), may suggest that the older group may have similar rotational kinematics to individuals with diagnosed rotator cuff impairment.

The differences that were observed in medio-lateral translation may suggest that the younger group keeps the lever (their humerus) closer to the body (the rotation centre) to increase the mechanical advantage. Minimizing the length of the moment arm reduces the amount of muscle force needed to elevate the humerus. Older individuals may have increased muscle atrophy, making it difficult to for the supraspinatus muscle to induce the same force than a person who is younger (Keller and Engelhardtet, 2013, Barnes et al., 2001).

There were significant differences between age groups during the initial 20% of motion in each of the three motion conditions. When muscle function is impaired, other muscles must compensate for the action. This was observed in several studies where there was increased activation of the deltoid and trapezius has increased activation to compensate for rotator cuff injury (Duc et al., 2014, Steenbrink, Carel, Meskers, Neilssen, and de Groot, 2010, Ludewig and Reynolds, 2009). This increase in compensatory muscle activity this could cause the humerus to track more superiorly as postulated in Steenbrink et al. (2010). In the current study, results of superio-inferior translation during the conditions of FF and AAC is dependent upon the motion. The average translation reported by Matsuki et al. (2012) in the superior direction was 2.1 mm; no SD was reported.

A cadaveric study that simulated supraspinatus paralysis concluded that impairment of the supraspinatus did not change normal joint kinematics or prevent full scapulohumeral abduction (McMahon et al., 1995). Although the motion observed in this current study was in-vivo, the results of McMahon et al. are similar with the ABD kinematic results observed in cadaveric shoulders. McMahon et al. (1995) observed no difference in kinematic values when altering the function of the supraspinatus muscle. These results could be applied to the results of the current study younger healthy shoulder motion to the shoulder motion of an older group with likely undiagnosed rotator cuff pathology based on their age. This could indicate that full range of motion of abduction may not be the best motion for determining the function of a supraspinatus muscle.

The current study documented significantly increased variability during the motion between age groups, specifically internal/external rotation, anterio-posterior translation and medio-lateral translation. The increased variability in the older group could be attributed to different motion patterns. For example, a study by Yano et al. (2010) using skin-based motion tracking of the scapula and humerus noted that there were two distinctive groups in terms of the initial phase of elevation where the scapula either rotated downward in 8 of their subjects when evaluating bilaterally, 8 subjects showed no downward scapular rotation at all. They also identified a third group, 5 subjects that showed opposing motion patterns between dominant and non-dominant arms. These distinctive movement patterns indicate that individuals can use different strategies to obtain the same result. Yano et al. (2010) observed that increased downward scapular rotation and reduced rotation from the humerus, and when there was no scapular rotation downwards, the action was primarily completed by the angle of elevation of the humerus, and both patterns would reach the same final motion goal.

The study by Nishinaka et al. (2008) reports that the translations were less than 1.7 mm for humeral abduction motions. The translations found in this study were larger and could be due to the differences in biplanar RSA techniques, joint coordinate system locations, the use of a non-subject-specific shoulder model, and differences in ABD motion recorded for analysis. For example, the current study evaluated motions up to approximately 90 degrees while the Nishinaka et al. (2008) study evaluated motions up to approximately 150° degrees. Additionally, the translational measurements by Nishinaka et al. (2008) were calculated from the centre of the glenoid to a point on the superior surface of the humeral head as opposed to the current study's methodology of calculating the difference between the AA the centre of the HH. Another difference in methodology that could contribute to differences in outcomes between the two studies is that the starting position was controlled in the study by Nishinaka et al. (2008), but not in the current study. This may have lead to the differences in results of translations during ABD between the two studies.

3.4.2 Comparisons between motion conditions

The kinematic motions of scapular plane tilt, internal/external rotation, anterio-posterior translation, medio-lateral translation and superio-inferior translation all exhibited significant differences when comparing motion conditions (ABD, FF, AAC). The amount of significant differences in the MANOVA indicate that these should be treated as completely separate conditions in three independent ANOVAs, one for each motion. The approach of separate ANOVAs for each motion has previously been used in a study by Bey et al. (2011).

Descriptions of scapulohumeral kinematics during ABD have been reported on in several studies (Matsuki et al., 2012, Bey et al., 2011Nishinaka et al., 2008). Bey et al. (2011) also evaluated FF; however, no previous studies have described AAC. To the author's knowledge, limited research has been published specifically looking at FF and AAC, thus these data presented is unique and could present ground work for future research into understanding the kinematics of the scapulohumeral joint for both healthy and injured shoulders.

3.2.3 Implications

Comparisons of the kinematics of the scapulohumeral joint in two different age groups yielded limited significant differences. This indicates that motion at the scapulohumeral joint is different between the two groups during ABD, FF and AAC. This result may assist clinicians evaluate motion at the scapulohumeral joint to assist in diagnosing shoulder pathologies such as impingement and rotator cuff tears. If differences are noted during diagnostic testing, further investigation into the cause of the divergent motion pattern is needed.

For researchers, using healthy, age-matched controls when studying scapulohumeral joint motion can ensure that the comparisons are free of the confounding variable of age. The purpose of this study was to observe and describe differences in scapulohumeral kinematics between age groups over three motions. Observing differences in the variability of motion indicate that there are some differences in how the individuals within each group move. This high variance within the groups may be due to the joint itself. Motion at the scapulohumeral joint is highly variable because it is a 6 degree of freedom joint, meaning several different combinations of rotations and translations at the scapulohumeral joint could lead to the same final result.

3.4.4 Limitations

Although trends in the scapulohumeral kinematics during flexion, abduction and combined motions were observed in this study, it is likely that the large variability between subjects made it more difficult to observe statistically significant differences between groups. This might be due to the relatively small sample size in the current study (Faul, Erdfelder, Lang and Buchner, 2007). Unfortunately, it was not possible to test a larger number of subjects. The motions were performed at a self-selected pace and verbally guided. These uncontrolled variables may have significantly altered the motion strategy used to facilitate the motion.

The biplanar fluoroscopic RSA data processing method is time consuming, making it difficult to obtain data in a quick and efficient fashion. At the current time, it would be unlikely that this technique could be used as a clinical tool due to the slow nature of data processing.

The younger and older age groups of this study may have been too similar in age for additional statistically significant results. It is more likely that significant differences in scapulohumeral kinematics would be found in a healthy, normal group over the age of 65. This older age group is more likely to have asymptomatic rotator cuff impairment (Milgrom, 1995, Bey, 2011). Additionally, it is more likely that more statistically significant differences in scapulohumeral kinematics will be observed between the younger group and a group of subjects over the age of 65.

3.4.5 Recommendations

Based on the results, it is recommended that further research be done comparing healthy individuals of different age groups to those with diagnosed rotator cuff pathologies, to determine if there are any differences in the scapulohumeral kinematics. Due to observations of significant differences in kinematics between younger and older age groups, employing an age-matched control when comparing kinematics in healthy and injured shoulders will reduce the influence of age on the results. Additionally, a majority of the kinematic variables were significantly different between the different motions performed at the glenohumeral joint; therefore the conditions should be treated as completely separate actions.

Collecting EMG data of rotator cuff muscles while the subject performs motion would indicate how the muscles are being recruited during the motion and how they differ based on age and motion performed. More specific information relating to muscle recruitment patterns could further help clinicians understand the underlying mechanisms for scapulohumeral motion, and variability in this motion.

3.5 Conclusion

Dynamic markerless biplanar fluoroscopic RSA was used to compare scapulohumeral kinematics between younger and older age groups during ABD, FF and AAC. This study provides important baseline data on scapulohumeral motion that will be useful to assist clinicians in making accurate diagnoses. The null hypotheses are that there are no differences in the angles and translations of the humerus relative to the scapula is accepted based on age group; therefore, the null hypotheses are rejected as significant differences between age groups were observed. Significant differences in the kinematics were observed based on condition, so the null hypothesis is rejected and the alternative hypothesis is accepted, meaning that ABD, FF and AAC are all different motions. The null hypothesis that the action would take longer in a healthy, older group is accepted for the ABD motion, but rejected for FF and AAC. Further study using this approach may help shed light on the motion in an impaired scapulohumeral joint due to its increased level of sensitivity in this methodology.

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Chapter 4

4 Comparisons of scapulohumeral kinematics before and after surgical intervention for a rotator cuff repair

This chapter describes and contrasts scapulohumeral kinematics in three subject groups: a group with supraspinatus tears (≤ 3 cm), a group that has undergone supraspinatus repair surgery and an age-matched healthy group with no shoulder pathology.

Abstract

Rotator cuff injuries impair scapulohumeral kinematics. Accurately describing the kinematic motion of the glenohumeral joint in all six degrees of freedom using a system to observe motion of the bones will allow clinicians to better understand what kinematic changes occur from supraspinatus tears and how motion is affected post-surgery. Three groups were observed, one being pre-surgical intervention for a supraspinatus tear (≤ 3 cm), another being 4-6 weeks post-surgical intervention, and finally, an age-matched control group were recruited. Kinematic data were collected using a markerless biplanar fluoroscopic radiostereometric analysis technique and manually matched to a generic shoulder model. Groups were compared against each other for the motions of abduction, forward flexion, and a combined motion termed arm across the chest. Significant differences were observed in all three movements. For example, there were significant differences in humeral abduction, medio-lateral translation and superio-inferior translation during abduction, internal/external rotation for forward flexion, scapular tilt and medio-lateral translation for the combined arm across the chest movement. This study the first of its kind to measure a combined shoulder motion in several subject groups. The markerless biplanar fluoroscopic radiostereometric analysis determined differences based on shoulder pathology and type of motion. Differences in scapulohumeral kinematics were observed between the healthy and pre-surgery groups. These results at 4-6 weeks post-surgery indicated scapulohumeral kinematics are variable and may provide useful information to clinicians regarding rehabilitation.

4.1 Introduction

A glenohumeral joint requires the support of soft-tissue to function properly. As a person ages, range of motion reduces, muscle atrophy occurs (Huang and Jung, 2015, Barnes et al, 2001). Rotator cuff tear rates increase in individuals over the age of 50 and the prevalence exceeds 80% as a person approaches 80 years of age; (Milgrom, Schaffler, Gilbert, and Van Holsbeeck, 1995, Hughes, Johnson, O'Driscolll, and An, 1999, Faulkner, Brooks, and Zerba, 1995).

Rotator cuff injuries hinder the mobility of the scapulohumeral joint kinematics during motion (Ludewig and Reynolds, 2009, McClure, Michener, and Cardunna, 2006, Mell et al., 2004, Struyf, Nijs, Baeyens, Mottram, and Meeusen, 2011). Individuals with full-thickness supraspinatus tears show additional upward rotation of the scapula during arm elevation to compensate for the rotator cuff functional impairment (Ludewig and Reynolds, 2009). Paletta, Warner, Warren, Deutch, and Altchek (1997) performed a static biplane radiographic analysis of shoulder kinematics and noted that healthy control subjects' humeral heads translated inferio-posteriorly in relation to the glenoid centre, and that subjects with a supraspinatus tear's humeral heads translated superiorly and anteriorly during arm elevation. After 2 years post-surgical intervention, the subjects had translations that were similar to those in the healthy, normal group (Paletta et al., 1997).

The surgical intervention for supraspinatus tear involves reattaching the muscle. The amount of invasiveness of the surgery depends which technique a surgeon performs. Ghodadra (2009) acknowledged that the open technique has good patient outcome rates, however, there are disadvantages in terms of anterior deltoid dysfunction and postoperative pain. In a mini-open surgery, some of the arthroscopic portals are increased in size, and some of the time and exposure for deltoid-splitting is limited, minimizing trauma at the surgery site. The trend in current surgical practice leans towards minimally invasive arthroscopic surgery to lower the risk of complications such as stiffness, infection and deltoid avulsions (Ghodadra, 2009). Either way, undergoing a surgery to repair a supraspinatus tear will be traumatic to the scapulohumeral joint.

Additionally, the suture technique is a factor in the healing of the supraspinatus repair (Pennington et al., 2010, Tashjian et al., 2010, Pauly, Gerhardt, Chen, and Scheibel, 2010). The additional stitching in the double row technique allows for more contact between the torn sides of the muscle, increasing the anatomical footprint of the repair (Pauly et al., 2010, Pennington et al., 2010, Burkhart and Cole, 2010). This is thought to lead to improved biomechanical quality of repair (Ghodadra, 2009).

Supraspinatus tear repair surgery has limited effectiveness. Many reports have indicated that up to 50% of supraspinatus repairs will fail (Miller et al., 2011, Chung, Oh, Gong, Kim, and Kim, 2011, Papadopoulos, Karataglis, Fotiadou, Christoforidis, and Christodoulou, 2010). Some of the factors leading to a failed repair include low bone mineral density, fatty infiltration of the muscle, degeneration of the muscle tissue, amount of retraction in the initial tear, and the age and health of the patient (Chung et al., 2011, Miller et al., 2011). The size of the anatomical footprint of the muscle restored could also be a factor when a repair fails, however, with the common use of the double row repair technique, restoration of the anatomical footprint of the supraspinatus is maximized (Miller et al., 2011). Additionally, Koo Parsley, Burkhart, and Schoolfield (2015), identified additional factors that lead to increased stiffness after rotator cuff repair, including calcific tendonitis, adhesive capsulitis, and PASTA (partial articular surface tendon avulsion).

Age has complicated influence on rotator cuff tears. As a person ages, several other factors of a person's healthy may become co-factors into leading to a tear, such as increased osteoclast activity, lowered bone mineral density, medication use, and diabetes (Miller et al., 2011, Chung et al., 2011, Tashjian et al., 2010). Chung et al. (2001) observed that younger individuals have more successful recovery after a rotator cuff repair surgery than older individuals. The quality of muscle tissue decreases as a person ages due to increased fatty infiltration and muscle atrophy which decrease healing rate (Laron, Samagh, Liu, Kim, and Feeley, 2012, Faulkner et al., 1995).

Similar studies have compared scapulohumeral kinematics using biplanar fluoroscope RSA. Bey, Peltz, Ciarelli, Kline and Devine (2011) observed scapulohumeral kinematics in abduction following a rotator-cuff repair. This longitudinal study followed subjects following a rotator cuff repair from 3 months following surgery to 24 months following surgery. It was determined that scapulohumeral kinematics are not fully restored to healthy scapulohumeral kinematics.

4.1.1 Rationale

This study describes and compares the scapulohumeral kinematics of simple and combined motions between groups of individuals pre- and post-surgical intervention for a rotator cuff tear with a healthy, age-matched control group. The null hypotheses for this study are that there will be no differences in kinematics between any three groups for all three actions observed, the motions will take the same amount of time to complete, and the variability for each of the three groups will be equal. The results may assist clinicians to determine rehabilitation protocols for patients and it may provide insight into the high prevalence of re-tear rates post-surgical intervention for rotator cuff tears by creating a baseline measure as soon as possible post-surgery.

4.2 Methods

4.2.1 Participants

This study was approved by the University of Western Ontario's Research Ethics Board (certificate #15278) and all participants provided informed consent before data collection. Four healthy subjects between the ages of 50-52 (average 50 years old, 2 male and 2 female) with no history of shoulder dysfunction and no regular use of analgesia were used as the healthy older adult age control group. The pre-surgical group consisted of three participants (2 male and 1 female, average age of 50, range 50-52 years old) with a supraspinatus tear classified as small or medium by an orthopedic surgeon (≤ 3 cm). The post-surgery group consisted of five subjects (4 male, 1 female, average age of 51, range 47-55) between 4-6 weeks post-surgical intervention for a supraspinatus tear. Exclusion criteria for the groups included pregnant or nursing women, radiation workers, two or more high-exposure radiological procedures in the past year, previous shoulder or arm surgery, or neurological dysfunctions.

4.2.2 Data collection

Participants attended a fluoroscopy data collection session in the Wolf Orthopedic Quantitative Imaging Laboratory (WOQIL) at the University of Western Ontario, London, Ontario. These sessions were conducted by a trained radiography technician. Subjects wore a sleeveless top, and bottoms of their choice, and were draped in a lead skirt. Subjects sat on a stool while performing shoulder abduction (ABD) and forward flexion (FF) up to approximately 90° of humeral elevation from the ground.

The subjects assumed a starting position with their body facing forward, their right elbow flexed to 90°, their upper arm touching the side of their body (torso) with neutral internal/external rotation. For the ABD motion, the subjects abducted the scapulohumeral joint from this starting position until their arm was at the level of their shoulder (approximately 90° humeral elevation from the starting position). For the FF motion, subjects began from the starting position and then rotated their right upper arm in the sagittal plane up to the level of their shoulder (approximately 90° humeral elevation from the starting position). For AAC, the subject assumes the starting position and performed a compound motion of shoulder flexion, adduction and internal rotation in which they moved their right hand and place it on their left shoulder.

The fluoroscopes were positioned to create a capture volume for the data collection of fluoroscopic video. The capture volume was unique for each individual in order to best-capture the scapulohumeral joint. Generally, one fluoroscope was positioned with the x-ray source anterio-superiorly towards the scapulohumeral joint and the second fluoroscope x-ray source was positioned anterio-medially. A technician recorded images of the scapulohumeral joint during these actions using two convergent fluoroscopes (30 Hz, SIREMOBIL Compact L; Siemens AG Medical Solutions, Erlangen, Germany). The subjects were asked to perform the actions at a slow pace.

4.2.3 Processing

Data were processed as outlined in Chapters 2 and 3 of this document.

4.2.4 Statistics

One analysis of variance (ANOVA) was calculated for each motion condition (ABD, FF, and AAC) using SPSS® (IBM, Statistics 23), where statistical significance was determined at the $p < 0.05$ level. The ANOVAs were 3×69 independent samples analysis using two factors: group had three independent levels (control, pre-surgery, and post-surgery) and kinematics in six degrees of freedom at each 10% of the trial (6 degrees of freedom x 10 time points = 60) and average overall variance of each of the kinematic variables (9). This was calculated for each 10% of motion (ABD, FF, AAC). The average and standard deviations were calculated for the amount of time to maximum action for each of the groups for each motion. An ANOVA with significance set at $p < 0.05$ was calculated to determine if there were statistically significant differences between the groups for the amount of time to peak motion for each group. Tukey HSD Post-hoc analyses were completed to determine pairwise significance between groups and conditions for kinematic variables.

4.3 Results

The motion patterns demonstrate that rotations follow similar trends although the amount of excursion varied across groups. There is a trend towards less rotation post-surgery compared to both the pre-surgery and healthy shoulder groups. The amount of ABD during all three motions was greatest in the healthy shoulders, illustrating a reduction in abduction with an impaired supraspinatus muscle, both pre-surgery and early post-surgery. Translations were greater in ABD and AAC and less in FF.

All three groups had significant differences in kinematics during motion. The healthy group took the least amount of time for each motion, while the pre-surgery group took the longest. All groups showed statistically significant differences with each other based on the results from the Tukey Honestly Significant Difference results (Table 4-1). On average, the old healthy group took 2.1 ± 0.5 s, while the pre-surgery group took on average 4.2 ± 1.0 s and the post-surgery group took 3.1 ± 1.0 s on average to reach total motion for all three trial conditions.

Statistically significant differences occurred most often during ABD, where differences were found in abduction angle in the healthy group was significantly larger than the other two groups. Translations were small in the majority of motion, where the largest differences in means can be seen in the anterio-posterior translations (Figure 4-1, 4-2; Tables 4-2 to 4-4, 4-6 to 4-10). The differences were smallest when comparing post-surgery means to pre-surgery means of motion during all three motion conditions. Full descriptive statistics can be viewed in the appendix. The following tables are the results that are statistically significant from the MANOVA analysis.

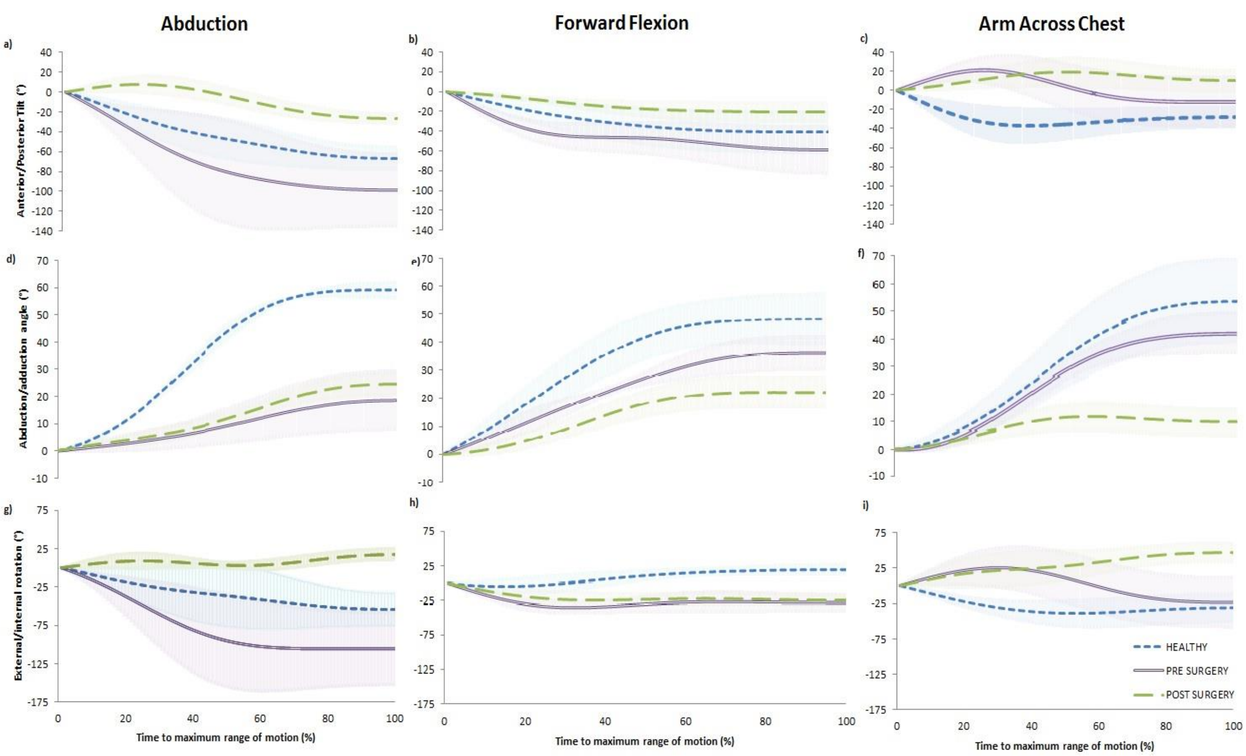

Figure 4-1: Mean rotations (line) for ABD (a,d,g), FF (b,e,h), and AAC (c,f,i) and standard error of measurement (shading) for the three subject groups (healthy controls (blue), pre- (purple) and post-(green) rotator cuff repair surgery).

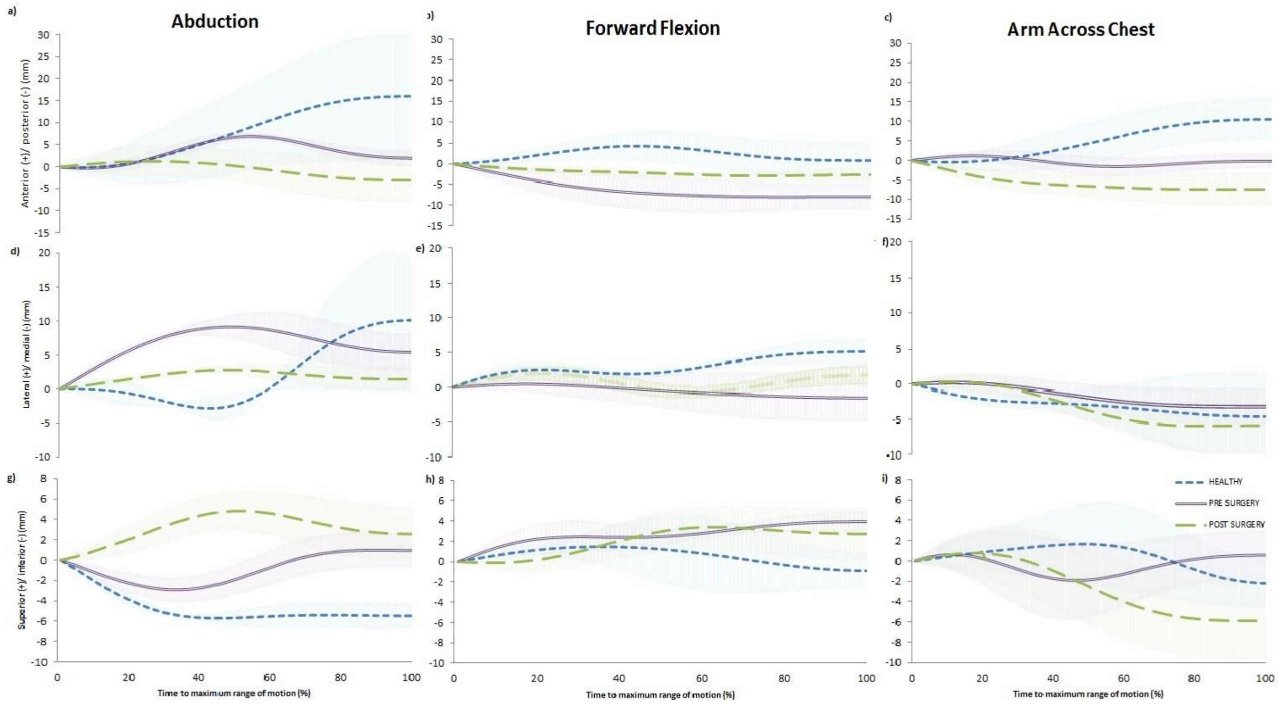

Figure 4-2: Mean translations (line) for ABD (a,d,g), FF (b,e,h), and AAC (c,f,i) and standard error of measurement (shading) for the three subject groups (healthy controls (blue), pre- (purple) and post-(green) rotator cuff repair surgery).

Table 4-1: Average time to maximum motion (s) and standard deviation for each group by condition. Significant differences were observed for each individual group by motion condition.

Motion	Healthy	Pre-surgery	Post-surgery
ABD	1.9 ± 0.4 [a]	4.3 ± 0.6 [a]	3.41 ± 1.0 [a]
FF	2.1 ± 0.6 [a]	4.4 ± 1.1 [a]	3.0 ± 1.0 [a]
AAC	2.2 ± 0.4 [a]	3.9 ± 1.2 [a]	2.9 ± 1.1 [a]

Significant differences for group (a)

4.3.1 ABD results

Significant differences were noted in humeral abduction for the rotational components of ABD (Table 4-2). Rotations seen during ABD demonstrated that the ABD angle of the humerus in relation to the scapula was much larger than that of the pre-surgery and post-surgery groups. From 30% of ABD to maximum motion, the healthy group has a significantly larger amount of ABD compared to both pre-surgery and post-surgery groups. The healthy group has significantly more ABD at 100% of motion than the other two groups.

Table 4-2: Humeral abduction means and standard deviations during ABD. Statistically significant differences were observed in the healthy group compared to the other two groups at each is the time points, no differences were found when comparing the pre-surgery and post-surgery groups during humeral abduction.

Percentage of motion (%)	Healthy	Pre-surgery	Post-surgery
30	20.85 ± 1.60	4.43 ± 6.28 [a]	5.74 ± 5.05 [a]
40	32.50 ± 3.30	6.55 ± 8.21 [a]	8.27 ± 4.93 [a]
50	43.44 ± 3.66	9.17 ± 10.68 [a]	11.74 ± 8.16 [a]
60	51.64 ± 4.18	42.91 ± 13.69 [a]	12.10 ± 13.42 [a]
70	56.89 ± 0.09	14.89 ± 15.77 [a]	19.78 ± 5.19 [a]
80	58.40 ± 2.24	17.03 ± 17.40 [a]	22.66 ± 6.51 [a]
90	58.94 ± 3.43	18.21 ± 18.29 [a]	24.13 ± 7.34 [a]
100	59.01 ± 3.76	18.57 ± 18.58 [a]	24.55 ± 7.59 [a]

Significant differences compared to healthy (a)

Translation differences between groups were seen in the medio-lateral and superio-inferior directions during ABD (Tables 4-3 and 4-4, respectively). In the medio-lateral direction significant differences were observed in the pre-surgery group compared to both the healthy group and post-surgery group. The humeral heads of the pre-surgery group translated laterally while the humeral heads of the post-surgery group had limited translation, and the humeral heads of the healthy group moved medially after 50% of action. In the first 70% of motion, humeral heads in the healthy group translated inferiorly and was significantly different than the humeral head translations in the post-surgery group which were superior (Table 4-4).

Table 4-3: Medio-lateral translation means and standard deviations during ABD. Significant differences are observed between healthy group and pre- and post-surgery at 30% and between pre-surgery at 60% of motion. Significant differences between the pre-surgery group and the healthy and post-surgery groups were observed at 10-30% and 50%, and between post-surgery at 60% of motion. Significant differences were observed in the post-surgery group compared with both groups at 30% and 40% of motion.

Percentage of motion (%)	Healthy	Pre-surgery	Post-surgery
10	-0.08 ± 1.82[b]	3.01 ± 0.72	0.73 ± 0.37[b]
20	-0.71 ± 2.17[b]	5.76 ± 0.82	1.49 ± 0.52[b]
30	-1.86 ± 0.64[b, c]	7.73 ± 0.80[a, c]	2.19 ± 0.36[a, b]
40	-2.80 ± 1.58[c]	8.85 ± 1.42[c]	2.68 ± 0.48
50	-2.33 ± 2.21[b]	9.14 ± 2.84[a]	2.80 ± 1.11
60	0.25 ± 0.41[b]	8.67 ± 4.36[a]	2. 53 ± 1.78

Significant differences compared to healthy (a), significant differences compared to pre-surgery(b), significant differences compared to post-surgery(c)

Table 4-4: Superio-inferior translation means and standard deviations during ABD. Significant differences are observed in the healthy group compared to the post-surgery group at 10%, 20%, 50-70% of motion. Significant differences were observed in the post-surgery group compared to the healthy group between 10-70% of motion, and compared to the pre-surgery group at 30-40% of motion.

Percentage of motion (%)	Healthy	Pre-surgery	Post-surgery
10	-2.14 ± 0.52 [c]	-1.26 ± 0.99	0.93 ± 1.40 [a]
20	-4.17 ± 0.63 [c]	-2.33 ± 1.52	2.13 ± 1.52 [a]
30	-5.21 ± 0.32[c]	-2.88 ± 1.78[c]	3.40 ± 2.96 [a, b]
40	-5.68 ± 0.27[c]	-2.70 ± 2.03[c]	4.40 ± 3.20 [a, b]
50	-5.68 ± 0.90 [c]	-1.84 ± 2.37	4.80 ± 3.54 [a]
60	-5.52 ± 1.32 [c]	-0.64 ± 2.70	4.52 ± 4.12 [a]
70	-5.42 ± 1.49 [c]	0.37 ± 2.87	2.81 ± 3.03 [a]

Significant differences compared to healthy (a), significant differences compared to pre-surgery (b), significant differences compared to post-surgery (c)

Variability of ABD motion for all three groups is reported in Table 4-5. The variability was significantly higher in anterior/posterior tilt in the pre-surgery group compared to the post-surgery and healthy groups, and the healthy group variability is significantly different than the pre surgery and post-surgery groups.

Table 4-5: Average variability and standard deviation for six degrees of freedom during ABD. Significant differences were observed between the healthy group compared to the pre- and post-surgery groups for all rotations and translations. Significant differences were also seen in the Pre-surgery group compared with the healthy and post-surgery groups for all three rotations.

Direction	Healthy	Pre-surgery	Post-surgery
Anterior/posterior tilt (°)	13.14 ± 5.00 [b]	35.32 ± 15.06 [a]	6.17 ± 2.06
Abduction/adduction(°)	1.42 ± 0.91[b]	6.11 ± 3.50 [a]	2.39 ± 0.89
External/internal rotation (°)	26.00 ± 10.99 [b]	42. 45 ± 17.78 [a]	6.50 ± 2.00
Anterior/posterior (mm)	8.58 ± 4.56 [b, c]	0.93 ± 0.39 [a]	3.47 ± 1.12 [a]
Lateral/medial (mm)	3.33 ± 3.52 [b, c]	1.60 ± 1.08 [a]	0.69 ± 0.51 [a]
Superior/inferior (mm)	0.65 ± 0.38 [b, c]	1.22 ± 0.44 [a]	1.75 ± 0.71 [a]

Significant differences compared to healthy (a), significant differences compared to pre-surgery (b), significant differences compared to post-surgery (c)

4.3.2 FF results

Significant differences were noted in only in internal/external rotation for the rotational components of FF (Table 4-6). Significant differences were found in internal/external rotation between 50% and 100% of motion in the healthy group compared to the pre-surgery group, and from 80% to 100% with the post-surgical group. Throughout the entire flexion movement, the healthy group maintained an internal rotation between 12° and 19°, while the pre-surgery and post-surgery groups maintain external rotation between -30° and -24° from its original location.

Table 4-6: Internal/external means and standard deviations during FF. Statistically significant differences were observed in the healthy group compared to the other two groups.

Percentage of motion (%)	Healthy	Pre-Surgery	Post-Surgery
50	12.02 ± 15.52 [b, c]	-30.17 ± 19.43 [a]	-26.16 ± 18.05 [a]
60	16.19 ± 12.52 [b, c]	-27.70 ± 23.54 [a]	-24.87 ± 17.97 [a]
70	17.97 ± 12.97 [b, c]	-27.14 ± 24.45 [a]	-25.06 ± 18.37 [a]
80	18.13 ± 14.59 [b, c]	-27.62 ± 22.74 [a]	-26.37 ± 17.06 [a]
90	17.77 ± 14.80 [b, c]	-28.07 ± 20.70 [a]	-27.60 ± 15.70 [a]
100	17.58 ± 16.19 [b, c]	-28.19 ± 19.81 [a]	-28.09 ± 15.23 [a]

Significant differences compared to healthy (a), significant differences compared to pre-surgery (b), significant differences compared to post-surgery (c)

Variability of FF motion for all three groups is presented below (Table 4-7). There were no significant differences in variability between groups for any of the 6 degrees of freedom.

Table 4-7: Average variability and standard deviation for six degrees of freedom during FF. No significant differences were observed between the subject groups.

Direction	Healthy	Pre-surgery	Post-surgery
Anterior/posterior tilt (°)	15.31 ± 5.68	14.78 ± 6.57	5.71 ± 3.28
Abduction/adduction(°)	6.70 ± 2.21	3.53 ± 1.69	3.81 ± 1.57
External/internal rotation (°)	7.12 ± 2.48	9.95 ± 3.56	7.51 ± 2.08
Anterior/posterior (mm)	2.80 ± 1.30	2.83 ± 0.93	0.70 ± 0.33
Lateral/medial (mm)	0.83 ± 0.45	2.13 ± 0.98	0.87 ± 0.26
Superior/inferior (mm)	1.91 ± 1.14	0.84 ± 0.38	1.66 ± 0.65

4.3.3 AAC results

Significant differences were noted in only in angular tilt for the rotational components of AAC (Table 4-8). Significant differences were also found in the medio-lateral translations during the first 20% of motion between the healthy group and post-surgery group (Table 4-9). Variability of AAC motion for all three groups was calculated and compared below in Table 4-10.

Table 4-8: Anterior tilt means and standard deviations during AAC. Statistically significant differences were observed in the healthy group and the pre-surgery group compared to each other and the post-surgery group.

Percentage of motion (%)	Healthy	Pre-surgery	Post-surgery
10	-7.68 ± 6.78 [b]	12.00 ± 7.57 [a]	0.61 ± 0.45
20	-13.65 ± 11.29 [b]	19.92 ± 17.27 [a]	1.95 ±2.14

Significant differences compared to healthy (a), significant differences compared to pre-surgery (b)

Table 4-9: Medio-lateral translation means and standard deviations during AAC. Significant differences were observed in the healthy group and the post-surgery group compared to each other and the pre-surgery group.

Percentage of motion (%)	Healthy	Pre-surgery	Post-surgery
10	-1.05 ± 2.06 [c]	0.93 ± 0.66	- 2.37 ± 2.52 [a]
20	-1.80 ± 3.64 [c]	1.11 ± 1.69	-4.07 ± 4.31 [a]

Significant differences compared to healthy (a), significant differences compared to pre-surgery (b)

Table 4-10: Average variability and standard deviation for six degrees of freedom during AAC. No significant differences were observed.

Direction	Healthy	Pre-surgery	Post-surgery
Anterior/posterior tilt (°)	13.90 ± 4.29	18.68 ± 8.30	10.05 ± 4.06
Abduction/adduction(°)	9.64 ± 4.85	4.03 ± 1.96	3.51 ± 1.52
External/internal rotation (°)	13.99 ± 6.40	28.46 ± 10.18	15.72 ± 5.39
Anterior/posterior (mm)	3.98 ± 1.62	1.44 ± 0.58	2.61 ± 1.07
Lateral/medial (mm)	2.68 ± 2.10	1.56 ± 0.67	1.97 ± 1.24
Superior/inferior (mm)	2.72 ± 1.10	2.59 ± 0.93	3.03 ± 0.98

4.4 Discussion

This study compared the scapulohumeral joint kinematics between pre- and post- surgery groups and a healthy age-matched control group. Several differences in kinematics were observed during ABD, and fewer were noted in FF and AAC. It is possible that these differences in kinematics compared to the healthy group could be due to pre- or post-operative pain associated with the motion (Scibek, Carpenter, and Hughes, 2009). Pain relief is a more common reason for surgical intervention for a rotator cuff tear than kinematic correction (Borgmastars, Paavola, Remes, Lohman, and Vastamaki, 2010, Watson and Sonnabend, 2002). It is possible that individuals try to reduce their pain by minimize the use of the rotator-cuff muscles and use another motion strategy to reach the same goal to minimize the pain felt during motion.

Alternately, the level of pain post-surgery may be a factor in the differences in translations and rotations about the GH joint between groups (Scibek et al., 2009). The subjects for the current study were 4-6 weeks post-operation, and may still have pain from the trauma associated with the surgery itself. This may alter their kinematics through compensation mechanisms (Watson and Sonnabend, 2002). Previous studies have shown that although most subjects that undergo rotator cuff repair surgery show an improvement in pain, 34% do not report an improvement in function (Watson and Sonnabend, 2002).

It has been previously established that shoulder pathology can lead to altered kinematics (Mahfouz, Nicholson, Komistek, Hovis, and Kubo, 2005, Ludewig and Reynolds, 2009). Some of the factors leading to this change in motion include changes in soft tissue properties, muscle activation or strength imbalances, increased muscle fatigue, and thoracic posture (Mahfouz et al., Michener, McClure, and Kardunna, 2003, Paletta et al., 1997).

The groups with supraspinatus tears and repairs many not be able to produce the same amount of power as those with a healthy supraspinatus because of muscle atrophy or structural damage. These changes have been observed as long as 2 years post-operation

(Bey et al., 2011). Pre-surgery, the structural deficiency of the supraspinatus may limit the amount of muscle that is functional. There may be additional deficits post-operatively due to the trauma of the surgical intervention itself. The joint may also be more difficult to move when injured due to stiffness from the injury (Koo et al., 2010).

The post-surgical timeline may also be a factor in the differences in kinematics in the surgical group compared to the other groups. The subjects in the post-surgery group in this study had their kinematic data captured 4-6 weeks post-surgery. Subjects were cleared for full activity in this study, even though this period is within the muscle re-education phase of rehabilitation, where muscle function may still be limited (Bey et al., 2011).

The motions were completed at a slow, self-selected pace and demonstrated that individuals with and healthy shoulders move in less time to reach their goal than those with impairment. The subjects with impaired supraspinatus muscles could have chosen to move more slowly to reduce pain during the motion.

4.4.1 ABD

During ABD, the healthy group has significantly more humeral abduction than the other two groups. This difference in rotation indicates that there is likely a different motion pattern to achieve 90° abduction in the healthy group compared with the other groups (Heuberer, Kranzl, Laky, Anderl, & Wurnig, 2015). This result is expected since the pre- and post-surgery groups have limited supraspinatus function. The pre-surgery group has a biomechanical disadvantage due to supraspinatus impairment. This may hinder force production of the supraspinatus, limiting the muscle's assistance in the ABD motion. Bey et al. (2011) evaluated differences in strength between subjects post-operatively compared to their contralateral shoulder and observed that a strength deficit is noticeable even after 2 years after surgery. Although the supraspinatus has been repaired in the post-surgery group, this group still demonstrated limited ABD. The trauma to the area and timing of post-operative assessment indicates that the muscle is in the re-education phase post-surgery and may not be fully rehabilitated and able to contribute fully to the action (Bey et al., 2011).

The lateral translation that was observed until 60% of the ABD motion in the healthy population was significantly different compared to both the pre- and post-surgery groups. A healthy rotator-cuff leads to stronger muscles to support joint. Mahfouz et al. (2005) estimate that the force at the GH joint in individuals with a healthy rotator cuff is larger during a box-lifting task than in the other groups. Also, Mahfouz et al. (2005) observed that the group with healthy rotator cuffs had greater average length of travel within the glenoid cavity than groups with impaired supraspinati. The intact supraspinatus in the healthy group may cause the variation of the ABD motion because of the larger path of travel in the healthy group (Mahfouz et al., 2005).

Translations observed in the post-operative group during ABD were significantly different than the inferior translation during ABD in the healthy group. This is different than the results noted in Bey et al. (2011), where no difference was observed between these groups. A major difference in the current study compared to Bey et al. (2011) was that the earliest post-operative measurement was taken at 3 months post-surgery. At this point it is possible that significant rehabilitation has occurred and likely changed the kinematics at the scapulohumeral joint versus the current post-operative timeframe. This 4-6 week post-surgery timeframe means that the muscles affected during the surgical intervention have not fully returned to normal kinematics. Bey et al. (2011) observed that deficits in muscular strength persisted after 24 months post-surgery. Paletta et al. (1997) and Bey et al. (2001) observed anterior translation during ABD in rotator-cuff impaired subjects, which is consistent with the results of the healthy group in the current study; however, these previous studies did not see as much translation in the impaired groups as in the current study.

4.4.2 FF

Substantial internal rotation was observed during FF for the pre- and post-surgical groups. This finding is consistent with previous studies that observed individuals with impaired rotator cuffs (Hebert, Moffet, McFayden, and Dionne, 2002). This could be due to increased activation and subsequent fatigue of other muscles, such as the deltoid, pectoralis minor and trapezius (Duc et al., 2014, Steenbrink, Carel, Meskers, Neilssen, and de Groot, 2010, Ludewig and Reynolds, 2009). This muscle imbalance could lead to increased dependency of the pectoralis minor causing additional internal rotation (Ludewig and Reynolds, 2009). There were no other significant differences noted during flexion. This could be because the contribution by the supraspinatus in flexion is minimal, and the upper trapezius, deltoid and pectoralis minor are able to compensate for the change in supraspinatus function to allow the motion to occur (Duc et al., 2014, Steenbrink et al., 2010, Ludewig and Reynolds, 2009). This may be the same reason for the increased variation of movement between groups

It is likely that the average movement patterns between groups increase in variation as more load is applied and the moment arm of the humerus in relation to the scapulohumeral joint gets longer. This increase in moment causes the muscles to adjust for the additional load to provide enough force to reach the motion goal. Although no studies have compared the variability of FF kinematics between pre- and post-surgery groups, Mahfouz et al. (2005) noted that the variation of motion patterns is greater in individuals with a rotator-cuff tears than healthy normal subjects during ABD.

4.4.3 AAC

Since the differences in kinematics were larger in the post-surgical group compared to the healthy group, there is a possibility that the post-surgical group was still not fully healed and could have still been on the cusp of the 0-4 week post-operative passive range of motion and scapular retraining phase in their rehabilitation (Bey et al., 2011). The trauma of the injury could possibly limit the motion at the joint. The ACC is a more complicated movement compared to isolated flexion or abduction, which may be the reason for seeing this result.

No significant differences were found, however large variation is observed in the internal/external component of this motion (Table 32). There was a large amount of variation between all of the subjects doing this motion, which could be a result of determining independent movement strategies. A study by Yano et al. (2010) observed two groups with distinct initial starting positions and a third group that had different starting positions contralaterally. These distinctive starting positions will create different movement patterns indicating that individuals can use different strategies to obtain the same result. The ball-and-socket scapulohumeral joint moves in 6 degrees of freedom, and there are many possible permutations of rotations and translations to obtain the same final result (Winter, 2009).

The healthy group has different initial motion during AAC compared with the pre- and post-surgery groups, however, as the motion continues, the pre-surgery and post-surgery groups' motion converged towards the healthy motion curve. Some studies have indicated a setting phase at the beginning of motion within the scapulohumeral joint (Inman, Dec, Saunders, and Abbott, 1944, Yano et al., 2010, Matsuki et al., 2012). This setting phase which is highly variable may be a factor in the differences during initial motion observed.

4.4.4 Limitations

Limitations associated with this study include a relatively small number of participants. Due to the long processing time and the invasive nature of the radiological techniques, it was not feasible to include more subjects. Additional assists with processing from lab technicians or an automated matching system could lessen the amount of time to obtain meaningful results, allowing for more data to be processed. Mahfouz et al. (2005) used an optimization algorithm to automatically adjust to the pose of the models at various orientations. Although in the Mahfouz et al. (2005) study used single plane fluoroscopy, a similar biplanar algorithm would greatly reduce processing time.

The post-surgery group measurements were collected between 4-6 weeks post-surgery. This may not be enough time for supraspinatus to fully contribute to the movement since it may be in the re-education phase of rehabilitation (Bey et al., 2011). The results of the current experiment could be misleading for this reason; however, this study describes motion during the early stages of rehabilitation post-surgery which provides a baseline measure for assisting in determining risk factors for re-tear.

4.4.5 Recommendations

Further research into this area is recommended. In order to determine whether these variable patterns are risk factor for re-tears, a larger longitudinal study is proposed to determine more specific relationships between post-surgery scapulohumeral kinematics and its effects on retear rate while controlling rehabilitation strategies. This information could provide clearer information for clinicians and researchers. It could yield insights into healing rates and comparisons between repair techniques to determine functionality and applicability of different treatment strategies for repairing shoulder function.

Obtaining more information about activation of the muscles of the rotator cuff during motion, through EMG analysis, may assist in describing compensation strategies for subjects with impaired supraspinatus muscles. It could also be used as a tool to determine recruitment pattern differences between healthy, pre-surgery and post-surgery groups.

Collecting data about muscular strength for the rotator cuff muscles would complement the data captured through the fluoroscopic biplanar RSA system. Combining the strength and EMG data can be informative for determining shoulder function changes with repair and comparing the different repair outcomes with the kinematics of a healthy population. This could lead to new hypotheses on why the re-tear rate is so high for rotator cuff repair surgery, and eventually help create protocols to reduce the risk of post-surgery repair failure.

4.5 Conclusions

This study compared the shoulder kinematics in a healthy population which was age-matched to pre-surgical and post-surgical supraspinatus tear groups. Biplanar fluoroscopic RSA was sensitive enough to determine significant differences between groups during motions that were both simple (isolated flexion and abduction) and combined AAC. Significant differences in scapulohumeral kinematics were noted predominantly during ABD, which is the primary function of the supraspinatus, however, some differences were also noted in FF and AAC. Statistically significant differences were observed in rotations and translations. Therefore, the null hypotheses were rejected and the alternative hypothesis that there were differences in scapulohumeral kinematics is accepted.

Often, as the motion progressed, the amount of variability increased. Additionally, the variability of the healthy, normal shoulder group was higher than the variability of the pre- and post-surgery groups for ABD, but not in FF or AAC. This means that the null hypothesis that there would be similarities in variability cannot be rejected.

Differences in time to maximum motion were statistically significant between all groups. The pre-surgery group took longer than the post-surgery and healthy normal groups, and the post-surgery group took longer than the healthy normal group. This means that the null hypothesis was rejected and the alternative hypothesis that the groups would take different lengths of time to reach maximum motion is accepted, where the pre-surgery group took the longest time to complete the motion, followed by the post-surgery group. The healthy group was able to complete the motion in the least amount of time.

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Chapter 5

5 Quantifying scapulohumeral rhythm using markerless biplanar fluoroscopic radiostereometric analysis

This study focuses on scapulohumeral rhythm during a variety of motions and use a novel method of measuring subacromial space using biplanar fluoroscopy and comparing accuracy of this method to previously established data.

Abstract

Scapulohumeral rhythm is used by clinicians to assist in the diagnosis of pathologic scapulohumeral motion. The use of markerless biplanar fluoroscopic radiostereometric analysis as a tool to calculate these measurements will provide very accurate measurements for the clinician in a research setting. Data were collected on four groups of subjects: a young, healthy group, a healthy older group, a group with rotator cuff tears and a group 4-6 weeks following rotator cuff surgery. Data were collected during abduction, forward flexion and arm across the chest motions. Scapulohumeral rhythm for the healthy younger group was around the expected 2:1 ratio of humerus to scapula rotations for abduction between 30° and 90° and forward flexion between 60° and 90°. Healthy younger (1.87 ± 0.45:1) and older groups (2.97 ± 0.20:1) had significantly less scapulohumeral rhythm compared to the group of subjects with supraspinatus tears (6.42 ± 3.10:1). No significant differences were observed when comparing the group post-surgical intervention with the other groups during abduction (1.83 ±0.20:1). During forward flexion, the scapulohumeral rhythm was significantly lower in the healthy younger group (1.97 ± 0.96:1) compared with the healthy older group (6.37 ± 1.43:1) and group of individuals with supraspinatus tears (9.86 ± 1.22 :1). Additionally, during forward flexion, the group with injured supraspinatus muscles had significantly higher scapulohumeral rhythm compared to the group that underwent supraspinatus repair surgery (6.50 ± 5.64:1). During the combined arm across the chest motion, there were no significant differences noted between groups. The results of this study indicate that markerless biplanar fluoroscopic radiostereometric analysis can measure scapulohumeral

rhythm differences in healthy and injured groups, allowing for comparisons between them.

5.1 Introduction

Accurate measures are important for diagnosing shoulder pathologies. A current method for quantifying shoulder pathologies is scapulohumeral rhythm (SHR). SHR is an examination evaluating the relative amount of rotation of the humerus and the scapula abduction. This method is quick, low cost and allows for useful clinically significant results in order to diagnose scapulohumeral impairment; however, it may have limited diagnostic accuracy. Measures of SHR using markerless biplanar fluoroscopic radiostereometric analysis (RSA) may provide more accurate results.

SHR is a tool to assist clinicians in determining shoulder pathology. Inman, Dec, Saunders, and Abbot (1944) determined the ratio of SHR in healthy shoulders is 2:1 for humerus motion during abduction (ABD) once the humerus is above 30° and in forward flexion (FF) once the humerus is above 60° (Figure 5-1).

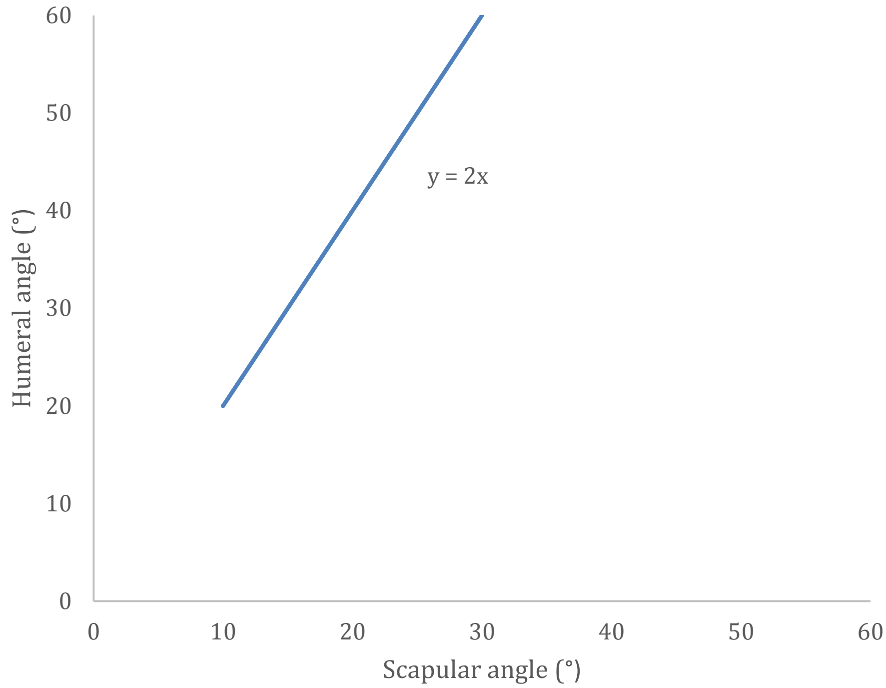

Figure 5-1: Example of scapulohumeral rhythm during abduction proposed by Inman et al. (1944). For the total elevation at the scapulohumeral joint, the humerus contributes to twice the amount of elevation as the scapula, exhibited by the equation of the line.

Several studies have reported that the initial phase of motion is highly irregular and that there is an initial setting phase of the scapulohumeral joint before this ratio is observed (Inman et al., 1944, Giphart et al., 2013, Scibeck, Carpenter, and Hughes, 2009). Giphart et al. (2013) measured SHR in healthy subjects using a markerless biplanar fluoroscopic RSA technique and calculated ABD SHR of 2.0 ± 0.4:1 and FF SHR of 1.1:1 ± 0.3:1. This method tracks the motion of the bones themselves and minimizes skin motion artifact that could affect the results. Using a markerless biplanar fluoroscopic technique requires a subject to undergo a CT scan before a subject specific bone model can be created which increases the amount of radiation a subject is exposed to. Scibeck et al. (2009) performed electrogoniometer measurements and observed that there was a positive correlation between amount of pain and the magnitude of the SHR for subjects with a rotator cuff tear. However, after a pain-relieving injection, their pain symptoms decreased, but did not correspond with a decrease in SHR (Scibeck et al., 2009). The use of surface-based electrogtoniometers to measure SHR may not be accurate enough to measure the rotations and translations of the underlying bones because of skin motion artifact.

5.1.1 Rationale

Markerless biplanar fluoroscopic RSA reduces error from skin motion artifact. The use of a subject specific model created from a CT scan to perform this technique increases the amount of radiation a subject is exposed to. Using a generic model to perform markerless biplanar fluoroscopic RSA will reduce the radiation exposure to a subject. The null hypotheses for this study is that SHR will be no statistically significant differences between pre-surgery compared to healthy younger, older and post-surgery groups, healthy younger and healthy younger groups would not be significant different from each other, and that healthy younger and healthy older groups would not be significantly different from the post-surgery group. The alternate hypotheses are that the SHR of the pre-surgery group will be statistically higher from the other groups, the healthy younger group has significantly lower SHR than the healthy older group, and that the healthy younger and older groups have significantly lower SHR compared with the post-surgery group.

5.2 Methods

5.2.1 Participants

This study was approved by the University of Western Ontario's Research Ethics Board (certificate #15278) and all participants provided informed consent before data collection. Data were collected on four groups of subjects. The first group included six healthy subjects between the ages of 18-22 (average 20 years old, 3 male and 3 female) and the second group consisted of four healthy subjects between the ages of 50-52 (average 50 years old, 2 male and 2 female) were recruited. Exclusion criteria for these groups were individuals who have no history of shoulder dysfunction and no regular use of analgesia.

The third group included individuals with small or medium (≤ 3 cm) supraspinatus tear of the right supraspinatus muscle classified by an orthopedic surgeon and had no other right shoulder pathology. Their ages ranged from 50-55 years of age (average 53 years). Two subjects were male and one was female. Exclusion criteria for these first three groups included pregnant or nursing women, radiation workers, two or more high-exposure radiological procedures in the past year, previous shoulder or arm surgery, or neurological dysfunctions. The fourth group was 4-6 weeks post-surgery for a small to medium supraspinatus tear on the right shoulder. This group had an average age of 51 (range from 47-55). It was composed of four male and one female subject. Exclusion criteria for this group include pregnant or nursing women, radiation workers, two or more high-exposure radiological procedures in the past year, and neurological dysfunctions.

5.2.2 Data Collection

Participants attended a fluoroscopy testing session in the Wolf Orthopedic Quantitative Imaging Laboratory (WOQIL) at the University of Western Ontario, London, Ontario. These sessions were conducted by a trained radiography technician. Subjects wore a sleeveless top and bottoms of their choice which was draped in a lead skirt. Subjects sat on a stool while performing shoulder abduction (ABD) and forward flexion (FF) up to approximately 90° of humeral elevation from a neutral starting position. Subjects also performed a compound action called arm across the chest (AAC).

The subjects assumed a starting position with their body facing forward, their right elbow flexed to 90° in the sagittal plane, their upper arm touching the side of their body (torso) with neutral internal/external rotation. For the ABD motion, the subjects abducted the scapulohumeral joint from this starting position until their arm was at the level of their shoulder (approximately 90° humeral elevation from the starting position). For the FF motion, subjects began from the starting position and then rotated their scapulohumeral joint in the sagittal plane up to the level of their shoulder (approximately 90° humeral elevation from the starting position). For AAC, the subject assumes the starting position and performed a compound motion of shoulder flexion, adduction and internal rotation in which they moved their right hand and place it on their left shoulder.

The technician recorded images of the scapulohumeral joint during these actions through two convergent fluoroscopes recording at 30 Hz (SIREMOBIL Compact L; Siemens AG Medical Solutions, Erlangen, Germany). The subjects performed the actions at a slow pace.

5.2.3 Processing

The fluoroscopy data were processed according to the methodology described in Chapters 2, 3 and 4.

In order to measure SHR, calculations must be completed to determine motion of the scapulothoracic and scapulohumeral components. Total arm elevation is equal to scapulothoracic rotation and scapulohumeral rotation. In order to measure the scapulothoracic component of motion, scapulohumeral elevation was subtracted from the total arm elevation (Giphart et al., 2013) (Equation 1). In this calculation, d_{sn} refers to displacement of the scapula at a specific point, p_{tn} was the total joint rotation at a specific time, p_{tn-1} was the total joint position at the previous point (Equation 1). The position of the humerus at a specific point in time was referred to as p_{hn} and the previous point was referred to as p_{hn-1}.

Equation 1: $d_{sn} = (p_{tn} - p_{tn-1}) - (p_{hn} - p_{hn-1})$

Linear regression was used to determine the ratio of humeral to scapular abduction for motion above 30° for ABD and AAC, and above 60° for FF.

5.2.4 Statistics

The data used to calculate SHR for ABD and AAC was the data over 30° of elevation and for FF was over 60° of elevation. These data were averaged based on group and condition. These data were analyzed using a 4x 1 independent samples analysis of variance (ANOVA) using SPSS ® (IBM, Statistics 23), where statistical significance was set at $p < 0.05$ for each motion (ABD, FF, AAC). Groups consisted of healthy younger, healthy older, pre-surgery, and post-surgery participants.

5.3 Results

No significant differences were observed between the young and pre-surgery groups, where the pre-surgical group had a significantly increased SHR compared to the young group in all three motions (Table 5-1).

Table 5-1: Average SHR and standard deviation for each group. Significant differences were observed during ABD between healthy-younger and pre-surgery groups and between pre-surgery and post-surgery groups. During FF, significant differences were observed comparing healthy-younger to healthy-older and pre-surgery groups, between healthy-older and post-surgery groups, and between pre-surgery and post-surgery groups. No significant differences were observed during AAC.

Motion	Healthy-younger	Healthy-older	Pre-surgery	Post-surgery
ABD	1.78 ± 0.45[c]	2.97 ± 0.20	6.42 ± 3.10[a,d]	1.83 ± 0.20[c]
FF	1.97 ± 0.96[b,c]	6.37 ± 1.43[a,d]	9.86 ± 1.22[a,d]	6.50 ± 5.64[b,c]
AAC	1.50 ± 0.48	5.82 ± 5.81	3.62 ± 1.95	10.41 ± 10.63

Significant differences compared to healthy-younger (a), significant differences compared to healthy-older (b), significant differences compared to pre-surgery (c), significant differences compared to post-surgery (d)

5.4 Discussion

The SHR in younger group had an average ratio of within the 2:1range for ABD and FF, similar to previous results (Giphart et al., 2013, Bey et al., 2011, Inman et al., 1944). The SHR was significantly lower in the healthy-younger group compared with the pre-surgery group for ABD and compared to both the healthy-older group and pre-surgery group during FF. The post-surgery group had an approximate SHR of 2:1 for ABD, but not for FF or AAC. The SHR of the post-surgery group was significantly different than the pre-surgery group for both ABD and FF, and significantly different from the healthy-older group during FF.

Anecdotally, the pre-surgery group appeared to shift their entire body during the motion. Since the rotations were calculated based on the initial starting position, the initial starting position of the scapula and humerus could have been different from the other groups, possibly causing the increased SHR results in this group compared to the other groups. In addition, the higher SHR in the pre-surgical group could be due to pain. For example, Scibeck et al. (2009) noted that increased pain corresponded to increased SHR. Over time, pain tends to decrease in post-surgical rotator cuff repair patients (Watson and Sonnabend, 2002); therefore, it is possible that reduced pain post-surgery may be a factor in reduced SHR compared with the pre-surgery group.

The SHR rhythm during ABD and FF for the younger healthy population was consistent with previously established results (Inman et al., 1944, Giphart et al., 2013, Scibeck et al., 2009). In the current study, the post-surgery group had a decrease in SHR compared to the pre-surgery group. This could be due to increased function post-operatively of the repaired supraspinatus, which could assist in the ABD and FF motion (Scibeck et al., 2009). Additionally, the ratios in the post-surgical group could be lower than pre-surgery due to stiffness in the joint post-surgery (Koo, Parsley, Burkhart, and Schoolfield, 2011). The data for the post-operative group was collected 4-6 weeks after the surgical intervention. This time period after surgery involves scapular retraining and the muscle re-education possibly leading to the limited humeral motion (Koo et al., 2010).

5.4.1 Limitations

Only the right shoulder was evaluated for this study. This limits the results application to pathologies and kinematics of the right shoulder only. Additionally, only a small sample-size was used for this study, which reduced the statistical power of this experiment.

The post-surgery group was measured at only 4-6 weeks post-surgery and limits the results to only one time point, where short-term and long-term effects are not observed. There may be some residual trauma at the area at this point after surgery, which may inhibit motion.

SHR was calculated between 30° and 90° for ABD and AAC, and between 60° and 90° for FF. Evaluating kinematics above 90° could provide further insight, and possible significant differences during higher elevation. Each 4th frame of data captured was digitized and used to calculate SHR, this reduced the time for data processing while providing acceptable results; however, more detailed data would provide more robust observations over the duration of the SHR calculation.

The only measures that may be calculated are of the humerus relative to the scapula. Kinematic measures of the scapula in relation to the thorax may provide additional insights into how the scapula itself is moving, helping to determine if trunk lean or scapular motion are factors in the higher SHR noted in the pre-surgical group. Having a larger capture, volume or a skin-based motion capture system, could help determine how much trunk lean plays a factor in motion about the scapulohumeral joint for the groups evaluated.

5.4.2 Recommendations

A longitudinal study may clarify the role the surgery plays and could begin to determine long-term surgical outcome from a kinematic perspective. Inclusion of the evaluation of kinematics of left shoulders as well as right shoulders would make the results more applicable to all individuals suffering from rotator cuff pathology.

Collecting data of the contra-lateral shoulder of all participants can help evaluate within subject differences. Developing and using an automated matching system could lessen the amount of time to obtain meaningful results, allowing for more data to be processed.

A method of using rib-based markers to define a thoracic coordinate system using biplanar fluoroscopy is currently under development at Imperial College, London (Giles, 2015). If this technique could be applied to the current data, it is possible to obtain measures of the scapula in relation to the thorax. This would allow for the determination of how much motion is occurring between those two areas and assess trunk motion as a factor of the SHR results.

Data processing could include more frames of digitized data to provide more detailed observations. In ABD and FF, the subjects could also perform elevation of the humerus until the subjects' maximum range of motion, allowing for additional comparisons between groups at the higher elevations of motion.

5.5 Conclusions

This study compared the SHR between four different groups. Significant differences were found during ABD and FF, but not AAC.

During ABD, the pre-surgery group had a significantly higher SHR than the healthy younger and older groups, but not compared to the post-surgery group, therefore the null hypothesis is rejected and the alternate hypothesis is accepted in comparison between pre-surgery and healthy younger and older groups, except for the comparison between pre-and post-surgery, where the null hypothesis is accepted.

During FF, the pre-surgery group had significantly higher SHR than the healthy younger group, therefore the null hypothesis is rejected, and the alternate hypothesis is accepted. The null hypothesis is accepted for the comparisons of SHR between pre-surgery and healthy older groups. The pre-surgery group had significantly higher SHR compared to the post-surgery group, rejecting the null hypothesis and accepting the alternate hypothesis. The healthy younger group had significantly lower SHR compared to the healthy older group, therefore the null hypothesis is rejected and the alternate hypothesis is accepted. No significant differences were observed between the healthy younger and older groups compared to the post-surgery group, therefore, the null hypothesis is accepted.

During AAC, no statistically significant differences were observed, therefore the null hypotheses were accepted.

This method of determining SHR was effective for comparing kinematics during ABD and FF. The use of a generic shoulder model in the processing of this data reduced the radiation dose to subjects while observing differences in SHR results between several different groups.

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Chapter 6

6 Conclusions

The purpose of this collection of studies was to further develop the knowledge of shoulder motion in order to better understand joint kinematics in healthy groups as well as groups with supraspinatus impairment and post-rotator cuff tear repair surgery. Using markerless bi-planar fluoroscopic radiostereometric analysis (RSA) with a generic shoulder model reduces the amount of radiation exposure to the subjects since the subject-specific model created by individual subject CT scans is omitted. These studies provided kinematic data of the scapulohumeral joint in six degrees of freedom with reduced radiation exposure to the subject during in-vivo data collection. In the future, this technique may help clinicians make decisions about whether a patient is a candidate for surgery, if the supraspinatus is likely to re-tear, or if their motion is within a normal range, based on their age.

Chapter 2 validated the use of a generic shoulder model for use with the biplane fluoroscope system for RSA. This reduces the radiation dose, thereby also reducing the risk associated with the radiation for subjects undergoing this type of data collection. The results indicated that there was an increase in variability compared with previously reported markerless biplanar fluoroscopic methods. Although this method had higher error than other biplanar fluoroscopic techniques, it is a recommended methodology compared to traditional biplanar fluoroscopic RSA because of the reduction in radiation exposure to the subject.

Chapter 3 compared the scapulohumeral motion of two different age groups during isolated flexion, abduction and combined motions. There were significant between the two groups during motion illustrating that the scapulohumeral motion is significantly different between healthy subjects in their 20s and healthy subjects that are 50 years old. This is important since the prevalence of rotator cuff tears increases with age, and is often present in 50-year-old subjects. Additionally, there was increased variability in the older group compared to the younger age group.

Chapter 4 compared the scapulohumeral motion in a group of healthy subjects and age-matched to a group of individuals with supraspinatus tears and a group of individuals post-surgical intervention for supraspinatus repair. Major differences in scapulohumeral motion were noted during ABD motion, such as differences in the time it took for groups to reach peak motion, humeral abduction, and medio-lateral and superio-inferior translations. As the motion progressed, the amount of variability within groups and between groups increased. This result indicated that supraspinatus injury does play a role in altered scapulohumeral kinematics.

Chapter 5 compared the scapulohumeral rhythm (SHR) and subacromial space between heathy and supraspinatus impaired groups, and provided some interesting results. For example, the group of individuals with supraspinatus tears had SHR magnitudes that were significantly higher than the young healthy age group during ABD and FF, as well as compared to the post-surgery group during FF. At 4-6 weeks post-surgery, it was evident that there were significant changes in SHR as it was not significantly different than the healthy groups.

This collection of studies lays the foundation for further directed study. Observing and recording kinematics of other age groups with healthy or undiagnosed pathology would be beneficial for clinicians for assisting in determining shoulder pathology diagnoses as well as providing an age-matched control for different age groups. As people age, the rate of healing is reduced, and the ability at the joint is also reduced. The ability of having an age-matched control and several ages will help determine if kinematics return to expected kinematics of healthy individuals of the same age group.

A longitudinal study using the current methodology while including several other variables such as EMG of the rotator cuff muscles, strength data, surgical intervention information such as size of tear, type of repair, and therapeutic rehabilitation protocol could all be included in a principle component analysis to determine what factors are of greater weight in failing rotator cuff repairs. This could then help surgeons choose techniques based on reducing the re-tear risk. Future directions of this work could also be to describe the kinematics of other shoulder pathologies such as frozen shoulder, bursitis, tendinopathy, and arthritis.

The results of the studies indicated that the markerless biplanar fluoroscopic RSA technique using a generic shoulder model for matching is a safer for subjects, due to the reduced radiation dose, and a viable alternative to current methodologies for traditional biplanar fluoroscopic RSA. This is the first study of this nature and further research into this area is warranted, specifically experiments observing muscle function in tandem with kinematic results, as well as comparing surgical intervention techniques. This information will assist clinicians to make more informed, specific treatment plans based on the needs of each individual patient, based on these studies.

Appendix

Average and standard deviation at each 10% of full motion for ABD, FF and AAC in all 6 degrees of freedom. Data includes the healthy younger population from Chapter 3, and the healthy older, pre-surgery and post-surgery groups from Chapter 4.

Motion (%)	Variable	Trial	Healthy-Younger	Healthy-Older	Pre-Surgery	Post-surgery
10	Scapular tilt	ABD	-5.45 ± 7.60	-11.51 ± 7.92	-18.31 ± 14.64	5.00 ±8.31
		FF	-14.59 ± 13.65	-11.86 ±13.53	-21.12 ± 8.34	-3.40 ± 1.53
		AAC	-5.91 ± 9.96	-7.68 ± 6.78	12.00 ± 7.57	0.61 ± 0.45
	Humeral abduction	ABD	3.12 ± 0.66	2.35 ± 3.03	1.21 ±2.22	2.00 ± 3.31
		FF	2. 48 ± 5.74	8.05 ±7.05	4.91 ± 4.21	0.98 ± 3.60
		AAC	-4.18 ± 3.39	4.42 ± 5.04	0.87 ± 2.14	2.14 ± 1.67
	Internal/ external rotation	ABD	-3.73 ± 4.86	-6.84 ± 8.40	-11.64 ± 11.12	4.10 ±8.12
		FF	-6.99 ± 19.39	-5.07 ± 16.38	-18.43 ± 8.61	-13.00 ± 13.75
		AAC	3.76 ±6.24	-9.94 ± 6.93	12.93 ±18.82	13.56 ± 26.83
	Anterio-posterior translation	ABD	0.51 ± 0.85	-0.04 ± 3.07	-0.27 ± 1.04	0.78 ± 4.13
		FF	1.49 ± 2.40	0.37 ± 0.93	-2.16 ± 2.36	-0.38 ± 0.52
		AAC	-1.52 ± 0.40	-1.05 ± 2.06	0.93 ± 0.66	- 2.37 ± 2.52
	Medio-lateral translation	ABD	-0.63 ± 2.44	-0.08 ± 1.82	3.01 ± 0.72	0.73 ± 0.37
		FF	0.73 ± 2.33	1.13 ± 0.80	0.40 ± 1.19	1.65 ± 1.29
		AAC	-1.85 ± 2.67	-1.62 ± 0.85	0.23 ± 1.04	0.94 ± 1.03
	Superio-inferior translation	ABD	0.35 ± 1.35	-2.14 ± 0.52	-1.26 ± 0.99	0.93 ± 1.40
		FF	-0.39 ± 0.94	0.42 ± 0.55	1.45 ± 1.46	-0.18 ± 1.65
		AAC	2.46 ± 2.38	-0.54 ± 0.92	0.62 ± 2.21	1.91 ± 1.16
20	Scapular tilt	ABD	-13.48 ± 17.53	-23.81 ± 15.56	-38.31 ± 38.27	7.54 ± 15.60
		FF	-31.03 ± 25.38	-23.38 ± 22.10	-36.69 ± 15.64	-8.02 ±1.72
		AAC	-16.25 ± 20.88	-13.65 ± 11.29	19.92 ± 17.27	1.95 ±2.14
	Humeral abduction	ABD	8.17 ± 2.69	10.83 ± 0.22	2.73 ±4.37	3.83 ± 4.60
		FF	7.09 ± 12.55	17.26 ± 12.14	10.32 ±6.21	3.77 ± 6.20
		AAC	-6.91 ± 7.15	6.48 ± 10.47	4.91 ± 4.47	5.37 ± 3.25
	Internal/ external rotation	ABD	-10.59 ± 12.57	-16.66 ± 22.55	-32.52 ± 36.11	8.26 ± 17.60
		FF	-13.47 ± 34.73	-5.23 ± 26.06	-30.90 ± 13.54	-22.67 ± 23.20
		AAC	4.70 ± 13.24	-18.23 ± 11.44	22.26 ± 13.24	23.12 ± 46.17
	Anterio-posterior translation	ABD	1.56 ± 0.66	0.87 ± 6.22	0.70 ±1.83	1.23 ± 6.17
		FF	2.71 ± 3.90	0.91 ± 2.02	-4.14 ± 4.30	-0.77 ± 0.66
		AAC	-3.42 ± 0.12	-1.80 ± 3.64	1.11 ± 1.69	-4.07 ± 4.31
	Medio-lateral translation	ABD	-1.68 ± 3.98	-0.71 ± 2.17	5.76 ± 0.82	1.49 ± 0.52
		FF	0.70 ± 3.31	1.67 ± 1.30	0.50 ±2.08	2.47 ± 2.02
		AAC	-3.15± 4.70	-2.46 ± 1.38	0.08 ± 1.72	1.06 ± 0.53
		ABD	0.71 ± 2.62	-4.17 ± 0.63	-2.33 ± 1.52	2.13 ± 1.52
		FF	-0.43 ± 1.25	1.04 ± 1.32	2.25 ± 2.43	0.25 ± 2.92

	Superio-inferior translation	AAC	3.86 ± 3.51	-0.65 ± 2.48	0.16 ± 4.50	2.14 ± 1.42
30	Scapular tilt	ABD	-23.41 ± 27.13	-34.27 ± 2.87	-57.00 ± 64.53	6.41 ± 17.33
		FF	-45.60 ± 33.46	-32.83 ± 26.97	-44.28 ± 20.56	-13.02 ± 5.47
		AAC	-28.21 ± 29.18	-17.31 ± 14.00	20.24 ± 27.15	3.64 ± 4.67
	Humeral abduction	ABD	15.35 ± 6.14	20.85 ± 1.60	4.43 ± 6.28	5.74 ± 5.05
		FF	13.53 ± 18.34	28.57 ± 18.26	15.68 ± 5.42	8.34 ± 7.72
		AAC	-6.82 ± 10.61	12.91 ± 15.63	11.91 ± 6.12	9.08 ± 5.10
	Internal/ external rotation	ABD	-18.93 ± 19.97	-24.88 ± 37.27	-55.87 ± 66.49	9.03 ± 19.13
		FF	-19.07 ± 43.40	-1.06 ± 26.90	-27.34 ± 25.60	-27.34 ± 25.60
		AAC	2.17 ± 47.72	-23.71 ± 16.90	25.29 ± 47.72	28.34 ± 54.73
	Anterio-posterior translation	ABD	3.14 ± 1.20	2.69 ± 8.95	2.84 ± 2.19	4.73 ± 3.63
		FF	3.36 ± 4.44	1.47 ± 3.23	-5.67 ± 5.61	-1.21 ± 0.69
		AAC	-4.91 ± 0.87	-2.00 ± 4.40	0.47 ± 2.73	-4.83 ± 5.01
	Medio-lateral translation	ABD	-2.22 ± 4.26	-1.86 ± 0.64	7.73 ± 0.80	2.19 ± 0.36
		FF	-.13 ± 2.68	1.76 ± 1.36	0.29 ± 2.67	2.13 ± 2.57
		AAC	-3.50± 5.43	-2.67 ± 1.85	-0.12 ± 2.10	0.21 ± 1.10
	Superio-inferior translation	ABD	0.83 ± 3.73	-5.21 ± 0.32	-2.88 ± 1.78	3.40 ± 2.96
		FF	-0.01 ± 0.92	1.77 ± 2.84	-2.44 ± 2.55	1.29 ± 3.62
		AAC	3.80 ± 3.11	-0.36 ± 4.72	-0.93 ± 6.12	2.76 ± 3.80
40	Scapular tilt	ABD	-33.99 ± 34.50	-42.03 ± 46.10	-71.86 ± 83.56	1.72 ± 16.98
		FF	-55.62 ± 37.69	-39.77 ± 31.44	-46.17 ± 23.70	-17.47 ± 10.89
		AAC	-37.90 ± 33.59	-19.18 ± 16.36	13.47 ± 35.13	4.91 ± 6.71
	Humeral abduction	ABD	24.30 ± 10.08	32.50 ± 3.30	6.55 ± 8.21	8.27 ± 4.93
		FF	21.26 ± 21.33	34.89 ± 8.78	320.80 ± 2.67	13.80 ± 8.78
		AAC	-3.37 ± 13.38	20.65 ± 20.22	20.38 ± 6.37	12.34 ± 6.94
	Internal/ external rotation	ABD	-28.15 ± 24.75	-30.84 ± 49.58	-77.27 ± 91.34	6.74 ± 13.54
		FF	-23.36 ± 46.85	5.70 ± 21.66	-33.73 ± 15.08	-27.76 ± 22.05
		AAC	-1.49 ± 22.90	-26.40 ± 24.22	20.82 ± 55.64	31.85 ± 53.25
	Anterio-posterior translation	ABD	4.98 ± 4.26	5.10 ± 11.04	5.23 ± 1.92	4.72 ± 3.03
		FF	3.43 ± 4.42	1.71 ± 4.40	-6.70 ± 6.33	-1.78 ± 0.77
		AAC	-5.14 ± 1.98	-1.48 ± 4.35	-0.59 ± 3.40	-4.94 ± 4.85
	Medio-lateral translation	ABD	-3.10 ± 3.52	-2.80 ± 1.58	8.85 ± 1.42	2.68 ± 0.48
		FF	-1.36 ± 1.11	1.86 ± 1.10	-0.09 ± 3.20	0.94 ± 2.50
		AAC	-2.98 ± 4.71	-2.34 ± 2.76	-1.12 ± 2.38	-1.33 ± 2.56
	Superio-inferior translation	ABD	0.69 ± 4.70	-5.68 ± 0.27	-2.70 ± 2.03	4.40 ± 3.20
		FF	0.69 ± 1.23	2.42 ± 4.93	2.39 ± 1.93	2.59 ± 4.00
		AAC	2.71 ± 1.86	0.10 ± 7.25	-1.78 ± 6.59	1.68 ± 4.89
50	Scapular tilt	ABD	-43.91 ± 37.98	-20.03 ± 18.43	-82.14 ± 89.76	-5.31 ± 15.58
		FF	-60.72 ± 39.03	-48.18 ± 27.34	-46.75 ± 26.61	-20.82 ± 15.67
		AAC	-42.66 ± 35.89	-44.65 ± 35.85	3.61 ± 40.32	5.07 ± 7.52
	Humeral abduction	ABD	33.97 ± 12.93	43.44 ± 3.66	9.17 ± 10.68	11.74 ± 8.16
		FF	29.24 ± 21.01	40.79 ± 19.30	25.65 ± 2.83	18.80 ± 4.30
		AAC	3.12 ± 15.57	28.43 ± 23.94	28.43 ± 5.92	14.39 ± 9.88

	Internal/ external rotation	ABD	-37.34 ± 29.06	-35.50 ± 56.14	-92.78 ± 102.91	3.77 ± 7.80
		FF	-25.85 ± 48.42	12.02 ± 15.52	-30.17 ± 19.43	-26.16 ± 18.05
		AAC	-2.93 ± 24.60	-26.66 ± 30.32	10.17 ± 60.71	36.57 ± 44.15
	Anterio-posterior translation	ABD	6.68 ± 7.87	7.80 ± 12.72	6.72 ± 1.09	14.80 ± 3.40
		FF	3.18 ± 4.40	1.28 ± 5.24	-7.34 ± 6.53	-2.48 ± 0.91
		AAC	-3.83 ± 5.54	-0.20 ± 3.69	-1.39 ± 5.17	-4.91 ± 4.68
	Medio-lateral translation	ABD	-3.92 ± 2.38	-2.33 ± 2.21	9.14 ± 2.84	2.80 ± 1.11
		FF	-2.49 ± 0.76	2.29 ± 0.81	-0.46 ± 3.88	-0.24 ± 2.30
		AAC	-1.92 ± 3.07	-2.16 ± 4.52	-1.83 ± 2.74	-2.95 ± 3.17
	Superio-inferior translation	ABD	0.47 ± 5.41	-5.68 ± 0.90	-1.84 ± 2.37	4.80 ± 3.54
		FF	1.34 ± 2.03	2.73 ± 6.80	2.48 ± 1.15	3.69 ± 4.29
		AAC	1.45 ± 0.83	0.44 ± 9.23	-1.84 ± 6.05	0.24 ± 5.19
60	Scapular tilt	ABD	-52.11 ± 37.59	-54.08 ± 25.30	-89.02 ± 85.00	-12.87 ± 14.28
		FF	-62.35 ± 38.77	-48.07 ± 38.84	-48.98 ± 30.05	-23.02 ± 18.73
		AAC	-42.47 ± 38.42	-20.23 ± 19.30	-4.90 ± 42.92	4.05 ±7.25
	Humeral abduction	ABD	42.91 ± 17.44	51.64 ± 4.18	42.91 ± 13.69	12.10 ± 13.42
		FF	36.98 ± 18.14	22.31 ± 10.94	30.02 ± 6.32	30.02 ± 6.32
		AAC	11.49 ± 17.44	34.99 ±26.29	11.49 ± 17.44	34.72 ± 6.82
	Internal/ external rotation	ABD	-45.34 ± 29.81	-40.24 ± 54.96	-101.36 ± 101.87	3.11 ± 10.97
		FF	-26.53 ± 50.29	16.19 ± 12.52	-27.70 ± 23.54	-24.87 ± 17.97
		AAC	-0.34 ± 24.37	-24.99 ± 33.00	-2.73 ± 62.68	43.25 ± 31.31
	Anterio-posterior translation	ABD	8.01 ± 11.09	10.56 ± 14.52	6.70 ± 0.66	-0.69 ± 7.49
		FF	2.93 ± 4.85	0.21 ± 5.57	-7.73 ± 6.26	-3.10 ± 1.22
		AAC	-1.44 ± 2.46	1.63 ± 2.73	-1.53 ± 3.30	-5.03 ± 5.42
	Medio-lateral translation	ABD	-4.62 ± 1.98	0.25 ± 0.41	8.67 ± 4.36	2. 53 ± 1.78
		FF	-3.17 ± 1.82	2.95 ± 1.78	-0.78 ± 4.67	-0.61 ± 1.88
		AAC	-0.60 ± 1.49	-2.12 ± 7.15	-2.43 ± 3.23	-4.12 ± 4.12
	Superio-inferior translation	ABD	0.46 ± 5.73	-5.52 ± 1.32	-0.64 ± 2.70	4.52 ± 4.12
		FF	1.70 ± 2.30	2.43 ± 7.60	2.83 ± 0.77	4.29 ± 4.47
		AAC	0.56 ± 0.67	0.31 ± 9.84	-1.21 ± 5.14	-1.03 ± 4.64
70	Scapular tilt	ABD	-57.91 ± 35.09	-59.71 ± 21.32	-93.86 ± 75.63	-19.35 ± 12.54
		FF	-62.39 ± 37.98	-50.40 ± 40.23	-53.81 ± 33.91	-24.36 ± 20.07
		AAC	-39.41 ± 41.80	-19.86 ± 18.94	-9.89 ± 43.81	2.46 ± 6.60
	Humeral abduction	ABD	49.79 ± 12.76	56.89 ± 0.09	14.89 ± 15.77	19.78 ± 5.19
		FF	43.42 ± 14.32	44.36 ± 17.60	33.37 ± 8.77	24.09 ± 11.7
		AAC	19.31 ± 19.93	39.61 ± 27.07	38.82 ± 9.00	14.58 ± 8.27
	Internal/ external rotation	ABD	-51.07 ± 28.79	-45.55 ± 47.44	-104.78 ± 94.49	6.10 ± 13.86
		FF	-26.20 ± 52.49	17.97 ± 12.97	-27.14 ± 24.45	-25.06 ± 18.37
		AAC	4.48 ± 22.59	-22.18 ± 32.69	-13.62 ± 62.07	50.24 ± 20.18
	Anterio-posterior translation	ABD	8.95 ± 13.29	13.06 ± 16.34	5.14 ± 1.46	-1.68 ± 8.58
		FF	2.87 ± 5.78	-1.08 ± 5.46	-7.96 ± 5.68	-3.37 ± 1.77
		AAC	1.08 ± 2.21	3.50 ± 2.03	-1.11 ± 2.97	-5.27 ± 6.75
	Medio-lateral translation	ABD	-5.17 ± 2.69	4.21 ± 5.66	7.64 ± 5.13	2.07 ± 2.33
		FF	-3.40 ± 2.32	3.52 ± 1.51	-1.05 ± 5.28	0.03 ± 1.92
		AAC	0.77 ± 0.77	-2.17 ± 9.99	-2.85 ± 3.71	-4.59 ± 6.18

	Superio-inferior translation	ABD	2.02 ± 7.77	-5.42 ± 1.49	0.37 ± 2.87	2.81 ± 3.03
		FF	1.79 ± 1.99	1.55 ± 6.97	3.31 ± 0.81	4.41 ± 4.53
		AAC	0.08 ± 1.23	-0.43 ± 8.91	-0.39 ± 4.42	-1.86 ± 3.66
80	Scapular tilt	ABD	-61.16 ± 32.58	-63.94 ± 17.66	-97.00 ± 67.64	-23.77 ± 10.48
		FF	62.06 ± 37.27	-51.80 ± 40.70	-56.41 ± 37.40	-24.86 ± 20.11
		AAC	-36.06 ± 44.98	-19.13 ± 18.41	-11.79 ± 43.97	1.08 ± 6.15
	Humeral abduction	ABD	53.94 ± 11.45	58.40 ± 2.24	17.03 ± 17.40	22.66 ± 6.51
		FF	47.75 ± 11.20	43.86 ± 17.03	35.30 ± 9.77	18.94 ± 8.31
		AAC	26.50 ± 19.80	42.23 ± 26.34	40.01 ± 10.92	13.84 ± 7.89
	Internal/ external rotation	ABD	-54.15 ± 27.21	-50.37 ± 38.26	-105.58 ± 87.04	11.28 ± 14.14
		FF	-25.81 ± 54.13	-18.13 ± 14.59	-27.62 ± 22.74	-26.37 ± 17.06
		AAC	8.84 ± 20.17	-19.31 ± 31.42	-20.25 ± 60.61	55.40 ± 15.03
	Anterio-posterior translation	ABD	9.52 ± 14.39	14.85 ± 18.56	3.40 ± 2.13	-2.48 ± 9.31
		FF	2.92 ± 6.72	-2.05 ± 5.18	-8.02 ± 5.07	-3.23 ± 2.56
		AAC	2.96 ± 2.14	4.84 ± 1.95	-0.58 ± 2.73	-5.46 ± 7.81
	Medio-lateral translation	ABD	-5.56 ± 3.56	7.75 ± 10.83	6.48 ± 4.98	1.70 ± 2.67
		FF	-3.37 ± 2.48	3.49 ± 2.15	-1.29 ± 5.54	1.14 ± 2.40
		AAC	1.93 ± 0.82	-2.50 ± 12.15	-3.06 ± 4.00	-4.55 ± 8.04
	Superio-inferior translation	ABD	0.97 ± 5.75	-5.42 ± 1.52	0.88 ± 2.81	3.30 ± 4.94
		FF	1.77 ± 1.49	0.45 ± 5.48	3.70 ± 1.14	4.31 ± 4.68
		AAC	-0.18 ± 1.98	-1.50 ± 7.25	0.22 ± 4.05	-2.23 ± 2.79
90	Scapular tilt	ABD	-62.42 ± 31.19	-66.12 ± 15.67	-98.48 ± 63.53	-25.97 ± 9.11
		FF	-61.87 ± 36.87	-52.45 ± 40.86	-58.41 ± 39.56	-25.06 ± 19.83
		AAC	-34.03 ± 46.89	-19.39 ± 18.18	-12.14 ± 43.97	0.35 ± 5.99
	Humeral abduction	ABD	55.71 ± 10.69	58.94 ± 3.43	18.21 ± 18.29	24.13 ± 7.34
		FF	49.86 ± 9.60	43.35 ± 16.96	36.02 ± 9.90	24.68 ± 12.24
		AAC	30.08 ± 20.07	32.90 ± 43.40	41.89 ± 11.92	13.32 ± 7.64
	Internal/ external rotation	ABD	-55.19 ± 20.05	-53.37 ± 31.96	-105.55 ± 82.63	15.70 ± 14.09
		FF	-25.70 ± 54.85	17.77 ± 14.80	-28.07 ± 20.70	-27.60 ± 15.70
		AAC	11.18 ± 18.40	-17.45 ± 30.69	-22.99 ± 59.65	57.92 ± 14.32
	Anterio-posterior translation	ABD	9.73 ± 14.73	15.74 ± 19.68	2.29 ± 2.47	-2.89 ± 9.61
		FF	2.99 ± 7.29	-2.50 ± 5.00	-7.99 ± 4.70	-2.99 ± 3.21
		AAC	3.92 ± 2.23	5.49 ± 2.08	-0.26 ± 2.63	-5.53 ± 8.31
	Medio-lateral translation	ABD	-5.77 ± 4.13	9.64 ± 13.76	5.69 ± 4.52	1.51 ± 2.78
		FF	-3.29 ± 5.52	3.84 ± 2.56	-1.43 ± 5.54	1.99 ± 2.78
		AAC	2.60 ± 1.09	-2.31 ± 13.25	-3.13 ± 4.08	-4.39 ± 8.97
	Superio-inferior translation	ABD	1.16 ± 5.74	-5.46 ± 1.51	0.97 ± 2.69	2.69 ± 5.10
		FF	1.73 ± 1.14	-0.33 ± 4.34	3.90 ± 1.46	4.22 ± 4.89
		AAC	-0.30 ± 2.49	-2.34 ± 5.96	1.32 ± 3.02	-2.32 ± 2.31
100	Scapular tilt	ABD	-62.68 ± 30.79	-66.70 ± 15.11	-98.86 ± 62.42	-26.90 ± 8.68
		FF	-47.74 ± 33.60	-52.62 ± 40.91	-58.97 ± 40.27	-25.10 ± 19.68
		AAC	-33.41 ± 47.49	-18.23 ± 18.40	-12.13 ± 43.97	0.15 ± 5.97
	Humeral abduction	ABD	56.13 ± 10.48	59.01 ± 3.76	18.57 ± 18.58	24.55 ± 7.59
		FF	50.43 ± 9.17	43.18 ± 147.01	36.14 ± 9.84	36.14 ± 9.84

	AAC	31.14 ± 20.09	43.63 ± 26.22	42.10 ± 12.19	13.15 ± 7.55
Internal/ external rotation	ABD	-55.32 ± 25.55	-54.53 ± 29.41	-105.46 ± 80.99	17.84 ± 14.26
	FF	-25.71 ± 32.58	17.58 ± 16.19	-28.19 ± 19.81	-28.09 ± 15.23
	AAC	11.81 ± 17.79	-16.82 ± 30.51	-23.60 ± 59.38	58.58 ± 14.41
Anterio-posterior translation	ABD	9.79 ± 14.76	15.97 ± 20.00	1.93 ± 2.57	-3.00 ± 9.68
	FF	3.01 ± 7.47	-2.61 ± 4.96	-7.96 ± 14.76	-2.87 ± 3.45
	AAC	4.19 ± 2.28	5.65 ± 2.12	-0.17 ± 2.61	-5.54 ± 8.44
Medio-lateral translation	ABD	-5.82 ± 4.32	10.54 ± 14.60	5.42 ± 4.29	1.45 ± 2.80
	FF	-3.25 ± 2.52	3.84 ± 2.69	-1.48 ± 5.51	2.29 ± 2.89
	AAC	2.81 ± 1.22	-2.33 ± 13.55	-3.14 ± 1.22	-4.32 ± 9.21
Superio-inferior translation	ABD	1.22 ± 5.74	-5.49 ± 1.51	0.95 ± 2.63	2.55 ± 5.11
	FF	1.72 ± 1.02	-0.60 ± 3.77	3.93 ± 1.58	4.19 ± 4.99
	AAC	-0.35 ± 2.66	-6.95 ± 9.92	-2.25 ± 1.65	0.87 ± 3.63

Curriculum Vitae

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Publications:

Hannon A, Michaud-Paquette Y, Turcotte RA, Pearsall DJ (2011). Dynamic strain profile of the ice hockey stick: comparison of player calibre and stick shaft stiffness. Sports Engineering 14(2-4)57-65.

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Hannon A, Michaud-Paquette Y, Pearsall D, Turcotte R. Slap and wrist shots: the effect of player calibre on stick strain gauge response. Canadian Society of Biomechanics, Kingston, Ontario, June 2010.

Hannon A, Michaud-Paquette Y, Pearsall D, Turcotte R. Usage of the ice hockey stick: Influences of stick mechanical properties on shooter kinematics. Education Graduate Student Society Conference, Montreal, Quebec, May 2010.